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Analysis of a pressurization system for airport's passenger walkways

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Analysis of a pressurization system for passenger walkways

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Fdo.: Alessandro Ferretti Fernández Fecha: 18/08/2023

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ANALISIS DE SISTEMAS DE PRESURIZACIÓN PARA PASARELAS DE EMBARQUE EN AEROPUERTOS.

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RESUMEN DEL PROYECTO

Introducción

La National Fire Protection Association (NFPA), es una entidad americana encargada de elaborar códigos técnicos y normativas para la prevención y protección contra fuegos e incendios. A través de sus códigos, son capaces de elaborar e implementar medidas eficaces para asegurar la seguridad de personas y bienes en una variedad de escenarios, instalaciones y edificios.

En particular, la NFPA ha elaborado una normativa especifica para edificios de terminales aeroportuarias, rampas de repostaje y pasarelas de embarque: la NFPA 415 [1]. Así, la NFPA es capaz de plantear todo un rango de medidas y estrategias para la prevención y mitigación de riesgos y daños relacionados con incendios en el ámbito aeroportuario. La creación de un código particular para este ámbito es de particular importancia por dos razones principales. En primer lugar, es importante recalcar la importancia de los aeropuertos a nivel logístico y económico. Estas infraestructuras son cruciales para un país para el desarrollo de varios sectores como el comercio, el turismo y la industria. Por lo tanto, un incidente grave en este tipo de infraestructuras puede tener un impacto muy amplio, en muchos ámbitos y de manera muy duradera que podría tener consecuencias graves para un país. Además, los aeropuertos son particularmente sensibles a incidentes. Se trata de lugares de mucho tránsito, con maquinaría muy compleja y especifica. Históricamente, se ha podido ver lo critico que es la seguridad y conformidad en este ámbito a través de grandes catástrofes aeronáuticas. Por estas razones, la NFPA ha decidido consagrar una normativa especialmente para aeropuertos, siendo códigos estrictos de cumplimiento riguroso.

En las versiones más recientes de la NFPA 415, aparece una sección que manda la obligación de tener sistemas de presurización en las pasarelas de embarque para proteger la

calidad del aire interior de humos, a raíz de un posible incendio exterior. Sin embargo, resulta chocante la falta de información y literatura relacionado con sistemas de presurización en pasarelas de embarque y su rendimiento, para un sector tan riguroso y vulnerable como son los aeropuertos. A raíz de esta falta de información sobre una obligación técnica marcada por una normativa así de importante, sale la motivación de este trabajo. El objetivo principal de este trabajo es dar respuesta a la NFPA 415 y analizar el cumplimiento de los objetivos marcados por la normativa por parte de un sistema de presurización, siendo estos mantener un ambiente sostenible y cómodo para los humanos dentro de la pasarela en caso de incendio exterior

Metodología

La metodología elegida para abordar este trabajo y avanzar hacia los objetivos marcados se divide principalmente en tres partes: investigación y revisión de datos, diseño y caracterización de sistemas de presurización y de pasarelas de embarque y finalmente modelado y simulación.

1. ***Investigación y revisión de datos.***

Para ser capaz de responder de manera eficaz a la normativa establecida en la NFPA 415, es necesario un conocimiento adecuado de las situaciones para las cuales el sistema de presurización debe proteger la calidad del aire interior. De esta manera, es necesario recurrir a un historial de incidentes acaecidos en aeropuertos relacionados con fuego para así poder investigar cualquier información que pueda permitir definir de manera precisa para que contexto debe funcionar el sistema.

De esta manera, se ha recurrido a “Aircraft Loading Walkways – Literature and Information Review”, un documento de The Fire Protection Research Foundations [2], que recopila descripciones e información respecto a una serie de incidentes y accidentes en aeropuertos en los que hubo incendios. Gracias a este documento, se ha podido extraer información, así entendiendo mejor el tipo de eventos e incidentes comunes en aeropuertos. Así, se han recopilado las principales causas de incendio para los casos vistos, en la figura 1. A partir de esta información se ha podido concluir que la principal causa de incidentes relacionados con fuegos con un 40 %, según los casos revisados en aeropuertos, son los fuegos de tipo *pool fire*, a raíz de derrames de combustibles. También son reseñables los fuegos de causados por fallos eléctricos, representando un 26,67 % del total. Sin embargo, para no agrandar en exceso el alcance del trabajo no se ha estudiado ese tipo de casos, dejándolo para futuras mejoras.

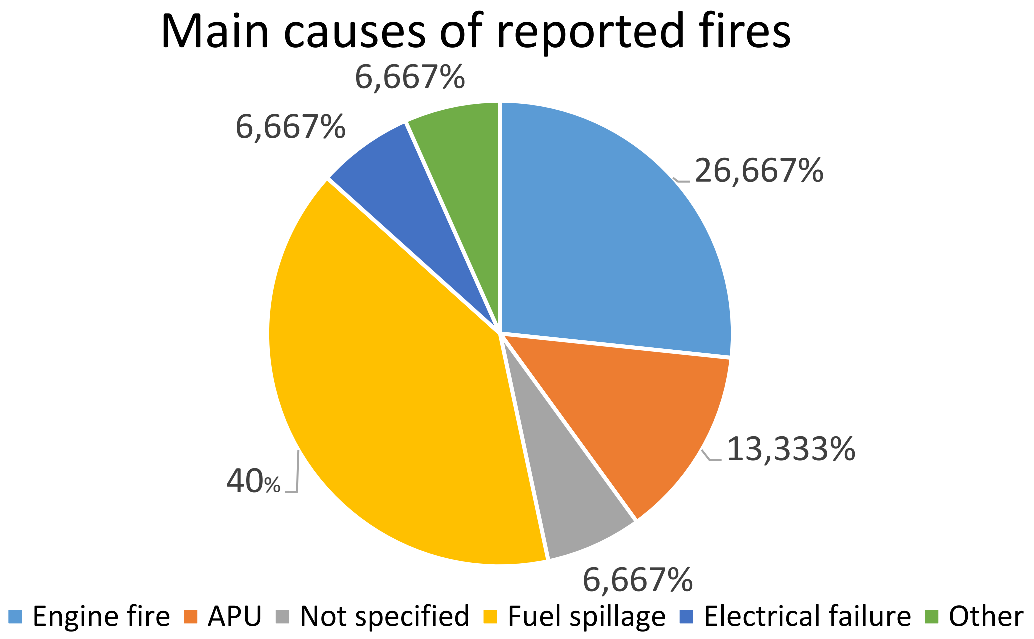

Fig.1. Principales causas de incendios en aeropuertos.

2. *Diseño y caracterización de sistemas de presurización y de pasarelas de embarque.*

Una vez definido el tipo de incidente contra el cual el sistema de presurización debe proteger, es también importante entender los parámetros importantes, tanto del sistema como de la pasarela, que pueden tener un impacto tanto en el diseño como el rendimiento del sistema.

El primer factor fundamental para un sistema de presurización es el caudal empleado. La variación del caudal del sistema implica una presión interior mayor y por tanto una mayor efectividad a la hora de mantener humos y gases tóxicos fuera de la pasarela de embarque. Sin embargo, el caudal tiene muchas otras implicaciones, ya que un caudal diferente puede tener como consecuencias diferentes temperaturas o una mayor o menor comodidad. Además de que, a mayor caudal, debería haber una mayor efectivad para proteger de humos, también implica un mayor consumo y menor ahorro. Así, resulta crucial evaluar el caudal utilizado que permita proteger el aire de la pasarela, a la vez que intentando reducir el consumo.

Además, también es importante la comodidad humana ya que es uno de los objetivos del proyecto. Uno de los factores a tener en cuenta para evaluar el confort, es la velocidad del aire. Como establece la normativa ANSI/ASHRAE Standard 55-2017 [3], la velocidad máxima para garantizar el confort humano en interiores es de 0,5 m/s. A su vez, como se estipula en la norma ISO 7730 [4], las velocidades optimas para el confort humano están comprendidas entre 0,15 y 0,25 m/s. Así, se ha decidido probar sistemas de presurización que impliquen velocidades de aire comprendidas entre 0,15 y 0,5 m/s, para poder garantizar el confort a la vez que se intenta mantener una calidad optima del aire. Para traducir estas velocidades a caudal, se ha empleado la siguiente formula:

$$Q = w \cdot h \cdot v$$

Siendo Q el caudal, w y h la anchura y altura interior de la pasarela y v la velocidad del aire. De esta manera, se ha obtenido un caudal de 3000 m^3/h para una velocidad de 0,15 m/s y un caudal de 9800 m^3/h para una velocidad de 0,5 m/s. Así, se probará el sistema de presurización para todo el rango de velocidades adecuadas para mantener un buen nivel de comodidad para los pasajeros.

Además, también es de especial importancia la estimación del área de fuga de la pasarela de embarque. Por un lado, son por estas fugas por las cuales el humo y los gases externos se pueden filtrar más fácilmente al interior de la pasarela. Además, las fugas de este tipo también representan perdidas de carga del sistema de presurización. Las perdidas de carga implican caídas de presión progresivas a lo largo de la pasarela. Por eso particularmente su estimación, de manera a poder seguir manteniendo una presión positiva hasta el final del túnel. Para poder estimarlas, se ha hecho uso de "Handbook of Smoke Control Engineering" [5], que proporciona las tablas de las cuales se han obtenido las siguientes áreas de fuga:

· Muros externos de la pasarela (Túnel): 1,7·10-4 m^2/m^2

· Puerta doble entre terminal y pasarela: 0,0781 m^2

· Puerta de embarque de la pasarela: 1,2·10-3 m^2/m^2

3. *Modelado y simulación.*

Una vez se ha determinado el tipo de fuego contra el cual el sistema debe proteger la pasarela y variables clave como el caudal del sistema y las áreas de fuga de la pasarela, se ha procedido a la elaboración del modelo con el cual se van a elaborar las simulaciones.

Este modelo se ha realizado en el software Fire Dynamics Simulator (FDS). FDS es un software de dinámica de fluidos computacional (CFD) especializado en dinámica de fuegos para diferentes condiciones y entornos. Además de utilizar ecuaciones de dinámica de fluidos o de transferencia de calor como otros softwares CFD, FDS emplea adicionalmente otros modelos que permiten a los usuarios predecir el comportamiento de incendios y dinámicas complejas como el movimiento del humo o la propagación de las llamas. Al permitir simular escenarios de incendio complejos y modelizar el comportamiento entre el fuego, el flujo de aire y las estructuras, FDS se ha convertido en un software muy utilizado para analizar el diseño de planes de protección contra incendios y desarrollar estrategias de seguridad eficaces.

Para poder modelar eficazmente el escenario en FDS, se han debido hacer ciertas simplificaciones e hipótesis previamente. Por ejemplo, este ha sido el caso para el carburante introducido al modelo. El carburante más común es el queroseno, principalmente del tipo Jet A y A1. Sin embargo, en este estudio, para simplificar, no se tendrán en cuenta todos los componentes y se utilizará un combustible simplificado. Según S. C. Moldoveanu, 2019 [6], el n-dodecano es uno de los principales componentes del queroseno y de los combustibles para reactores. El pirólisis del dodecano se ha utilizado comúnmente para comprender el comportamiento de los combustibles para reactores. Como tal, para el modelo simulado que se empleará, el combustible utilizado consistirá en n-dodecano.

Además, también se ha tenido que hacer una hipótesis en cuanto al tamaño del pool fire. Se estima que el sistema estudiado debe proteger en situaciones en las cuales la seguridad estructural de la pasarela no esta en peligro, es decir sin que esta se vea en vuelta dentro de las llamas. Por ello, se ha estimado que el diámetro máximo del fuego para el cual se harán simulaciones será para el cual la altura de llama alcanza la pasarela. Así, se ha obtenido un diámetro de 1,45 m, el cual se ha redondeado a 1,5 m. Por ello, se realizarán simulaciones para diámetros de como 0,5, 1 y 1,5 m. Los escenarios simulados están resumidos en la siguiente tabla.

Scenario	Smoke Control System	Pool Diameter
1	Pressurization (3000 m^3/h for 0,15 m/s)	0,5 m
2	Pressurization (9800 m^3/h for 0,5 m/s)	0,5 m
3	Natural ventilation	0,5 m
4	Pressurization (3000 m^3/h for 0,15 m/s)	1 m
5	Pressurization (9800 m^3/h for 0,5 m/s)	1 m
6	Natural ventilation	1 m
7	Pressurization (3000 m^3/h for 0,15 m/s)	1,5 m
8	Pressurization (9800 m^3/h for 0,5 m/s)	1,5 m
9	Natural ventilation	1,5 m

Tabla.1. Escenarios seleccionados para la simulación.

A continuación, se ha procedido a la propia elaboración del modelo, empezando por la geometría. Para esta se han seguido a grandes trazos las dimensiones del modelo de pasarela TB 45/26.5-2 de ThyssenKrupp. Se ha compuesto esta por 15 secciones de 3 m de larga cada una, estando cada una de estas dispuestas en una configuración de escalera, con 0,25 m de escalón entre cada una. La sección de esta tiene una anchura y altura interior de 2 y 2,5 m respectivamente. La anchura y altura exterior es de 2,5 y 3 m respectivamente. Además, también se ha modelado la entrada a la pasarela desde el aeropuerto (rotunda) y la entrada al avión.

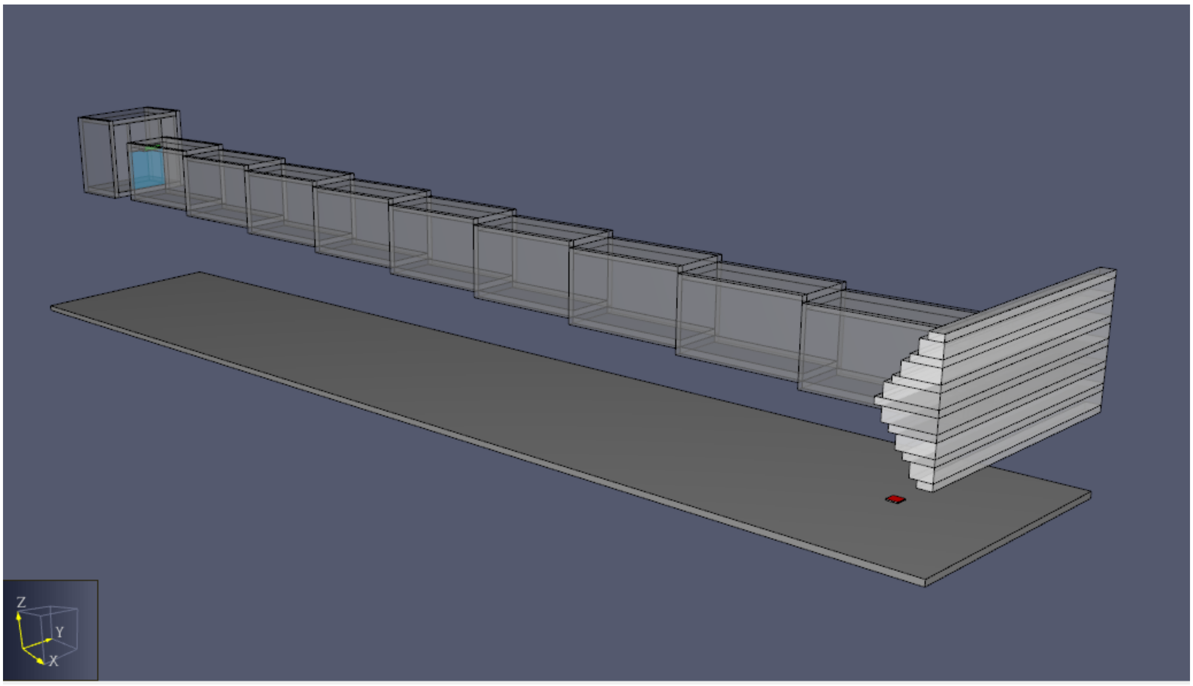

Fig.2. Modelo 3D de la pasarela.

Asimismo, se han modelado también las áreas de fuga de la pasarela acorde a los valores estimados previamente.

También se han introducidos dispositivos importantes como:

· 15 detectores de humo espaciados 3 m entre ellos, acorde a la norma.

· Un climatizador en la entrada de la pasarela (del lado del aeropuerto) cuya activación se da cuando al menos dos detectores se activen.

· En el caso de la ventilación natural, dos rejillas en el techo del túnel, en las secciones centrales.

Además, es de especial importancia para el modelo y la simulación, la definición de unas condiciones de contorno. Estas son indispensables para definir el flujo de aire, gases y la transferencia de calor y por tanto para determinar el comportamiento del térmico y fluido. En este caso, las condiciones de contorno aplicadas son:

· Caudal de aire en el climatizador. Este depende de lo definido para cada escenario.

· Condición de no deslizamiento en todas las superficies solidas (suelo, pasarela, avión, etc).

· Condición “Open vent”, que permite al aire entrar y salir del volumen de control.

· Ratio de perdida de masa, siendo este el ratio al que se quema el combustible.

Por lo tanto, falta estimar esta perdida de masa para completamente definir las condiciones de contorno. Para ello, se ha hecho recurso a las ecuaciones descritas en M. Muñoz et.al 2004 [7], que aportan una un método para su cálculo en el caso de gasolina. Se ha considerado apropiado aproximar este parámetro al de la gasolina debido a su similar comportamiento:

$$\dot{m}'' = \dot{m}''_{\infty}(1 - e^{-k'D})$$

$\dot{m}''$ *siendo el ratio de perdida de masa* $(kg\ s^{-1}\ m^{-2})$.

$\dot{m}''_{\infty}$ *siendo el ratio de perdida de masa maximo* $(kg\ s^{-1}\ m^{-2})$, *estimandose* 0,083 *para gasolina*.

k' *siendoun parametro constante* (m^{-1}), de valor 1,173 para la gasolina.

D *siendo el diametro del fuego* (m).

Finalmente, para la obtención de un modelo valido, es importante el desarrollo de una malla de suficiente calidad. Además, dependiendo de la zona, es importante controlar su tamaño de manera a tener elementos más reducidos en las zonas más críticas para mayor precisión y, asimismo, elementos más grandes en las zonas no críticas para menor peso computacional. Por ello, se han generado tres mallas para tres zonas distintas. Estas tres han sido validadas a través de un test de alineación de malla. La información importante de estas tres mallas está resumida en la siguiente tabla:

Malla	Nº de elementos	Dimensiones de los elementos	Location
1	280.000	0,05x0,05x0,05 m	0,5 m layer above ground and around pool fire.
2	42.560	0,25x0,25x0,25 m	Above mesh 1, heights between 0,5 and 10 n
3	275.200	0,25x0,25x0,25 m	Rest of domain
TOTAL	597.760		

Tabla 2. Parámetros principales de la malla del modelo.

Resultados

Antes de comenzar con el análisis de resultados, es importante definir los criterios utilizados para la validación del sistema de ventilación. Estos criterios se basan en los estipulado en el NFPA 92 [8]. Estos se dividen en dos partes:

· Criterio para gases tóxicos. El objetivo de este criterio es asegurarse de que los niveles de CO y CO_2 no resulten una amenaza para la salud humana. En el caso del CO, se calculará la dosis efectiva fraccional de CO en cada caso, esta no deberá superar los valores recogidos en la siguiente tabla.

Tiempo (min)	Limite		
	AEGL2	0.3	0.5
4	-	1706	2844
6	-	1138	1896
10	420	683	1138
15	-	455	758
30	150	228	379
60	83	114	190
240	33	28	47

Tabla 3. Límite de dosis efectiva fraccional de CO.

AEGL2, 0.3 y 0.5 son diferentes criterios, en este caso se usará el criterio 0.3 siendo este el más usado. Así, la dosis fraccional no deberá superar 1706. En el caso de CO_2 el criterio de validación es no superar el nivel de 30.000 ppm.

· Criterio de visibilidad: la visibilidad no deberá caer por debajo del límite de 10 m.

En cuanto a los resultados, se han separado en visibilidad, velocidad del aire, nivel de CO y nivel de CO_2. En cuanto a la visibilidad, se puede ver en la siguiente figura como la visibilidad es alcanza a ser inferior 10 m en cuanto el diámetro es superior a 0,5 m, antes de que el sistema de ventilación entre en acción.

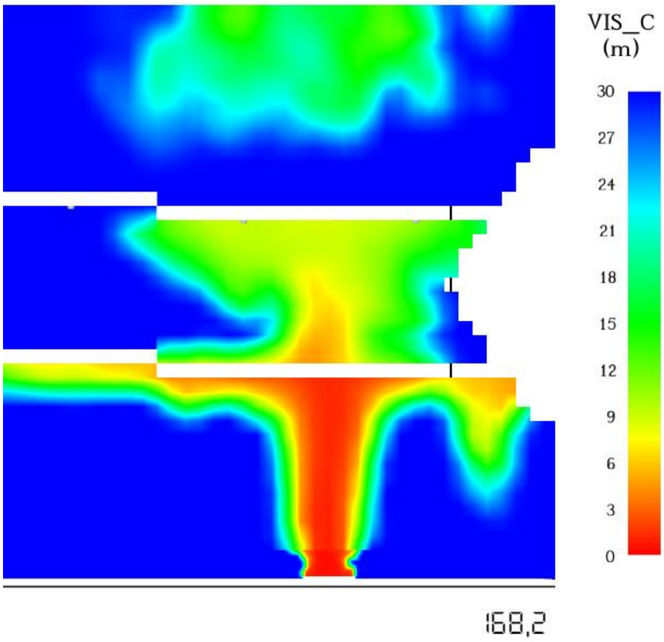

Fig.3. Contornos de visibilidad previos a la activación del sistema de presurización.

Sin embargo, es notable la mejoría en visibilidad una vez entra en acción el sistema de presurización, consiguiendo hasta para diámetros de 1,5 m, una visibilidad suficiente respecto al criterio previamente descrito.

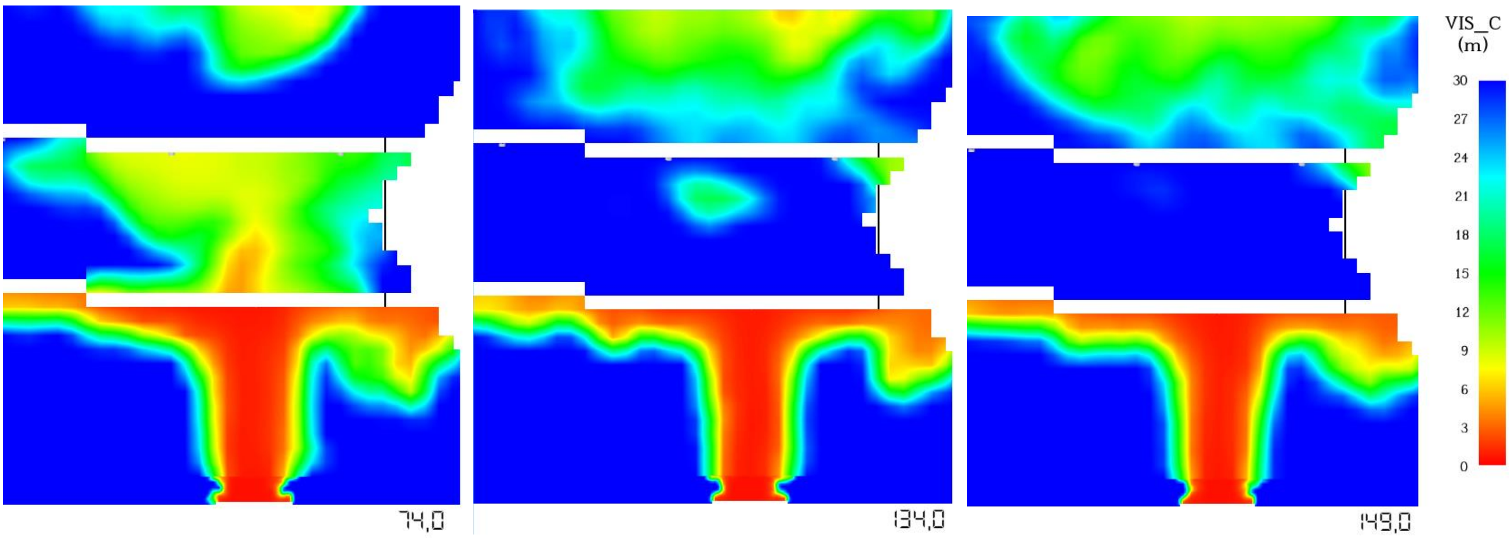

Fig.4. Contornos de visibilidad en el escenario 8 para t=74, 134 y 149 s.

Sin embargo, en el caso del sistema de ventilación natural este no es el caso. El sistema de ventilación natural es únicamente capaz de mantener una visibilidad superior a 10 m en el caso de diámetro de 0,5 m, pero no es efectivo tanto para un diámetro 1 m como de 1,5 m.

Además, es importante la velocidad del aire. Velocidades altas implican una mayor incomodidad para los pasajeros y visto que uno de los principales objetivos del sistema es mantener un entorno cómodo, se ha de controlar la velocidad. En este sentido, el sistema de ventilación natural si cumple ya que tiene velocidades notablemente inferiores a 1,5 m/s. Para el sistema de presurización con caudal de 3000 m^3/h, si se alcanzan velocidades cercanas al límite. Sin embargo, la zona donde ocurren estas velocidades es un área reducida cerca de la salida del climatizador. Este resultado es normal ya que la sección de salida es reducida, acelerando por tanto el aire. Este efecto es mayor para un caudal de 9800 m^3/h, en el que sí que resultan problemáticas las velocidades del aire, alcanzando en varios puntos prácticamente 3 m/s, el doble del límite para confort humano.

En lo que respeta a los resultados relacionados con la visibilidad, se han resumidos en la siguiente tabla.

		Previo a la activación		Despúes de la activación	
		Maxima perdida de visibilidad media (%/m)	Visibilidad minima (m)	Maxima perdida de visibilidad media (%/m)	Visibilidad minima (m)
Escenario	1	5,56	25,01	11,84	19,35
	2	5,712	24,86	11,222	19,9
	3	4,496	25,953	17,574	14,183
	4	27,096	5,614	16,65	15,02
	5	24,89	7,601	7,4	24,34
	6	34,307	0	38,244	0
	7	27,455	5,29	8,564	22,29
	8	27,608	5,153	0,123	29,89
	9	36,902	0	44,28	0

Tabla 4. Mínima Visibilidad para cada escenario, previo y después a la activación del sistema.

Los resultados están separados en dos partes, por un lado, los datos previos a la activación de los sistemas tanto de ventilación natural como de presurización y en el otro, los datos posteriores a dicha activación.

Para los casos de diámetro 0,5 m, se puede observar cómo se es capaz de mantener una visibilidad suficiente a lo largo de toda la simulación. Este no es el caso para el resto de los escenarios Se puede observar como para los diámetros de 1 y 1,5 m, se infringe el criterio de visibilidad ya que esta llega a caer por debajo de los 10 m. A pesar de esta caída de visibilidad, se ve como el sistema de presurización es capaz de cambiar la situación y recuperar niveles de visibilidad superior a 10 m para ambos escenarios, tanto con un caudal de 3000 m^3/h como de 9800 m^3/h. De esta manera queda validada la eficacia de este sistema a la hora de mantener una visibilidad segura en caso de fuego exterior. Sin embargo, no ocurre lo mismo para el sistema de ventilación natural. Este es incapaz de mantener buena visibilidad, alcanzando incluso la visibilidad nula en los casos 6 y 9, quedando así descartado como una opción valida para proteger la pasarela en caso de incendio.

Finalmente, quedan por analizar los datos relacionados con el nivel de gases tóxicos. En el caso del monóxido de carbono, se ha elaborado la siguiente tabla. En esta se presenta la dosis fraccional obtenida junto a su intervalo de confianza.

Escenario	1	2	3	4	5	6	7	8	9
FED_{CO} obtenido	0,0103	$5{,}79 \cdot 10^{-3}$	0,0569	0,0204	$8{,}49 \cdot 10^{-3}$	0,192	0,0330	$8{,}33 \cdot 10^{-3}$	0,253
Intervalo de confianza FED_{CO}	$[6{,}70 \cdot 10^{-3}; 1{,}39 \cdot 10^{-2}]$	$[3{,}77 \cdot 10^{-3}; 9{,}56 \cdot 10^{-3}]$	$[3{,}70 \cdot 10^{-2}; 7{,}68 \cdot 10^{-2}]$	$[1{,}33 \cdot 10^{-2}; 2{,}75 \cdot 10^{-2}]$	$[5{,}52 \cdot 10^{-3}; 1{,}15 \cdot 10^{-2}]$	[0,125; 0,317]	$[2{,}15 \cdot 10^{-2}; 5{,}45 \cdot 10^{-2}]$	$[5{,}41 \cdot 10^{-3}; 1{,}12 \cdot 10^{-2}]$	[0,164; 0,341]

Tabla 5. Dosis efectivas de CO obtenidas para cada escenario.

Como se observa, todos los resultados están muy alejados del valor limite de 1706, así afirmando la efectividad de los sistemas a la hora de mantener un nivel bajo de CO.

Ocurre igual respecto a los niveles de CO_2. La máxima concentración de este gas obtenida se da en el escenario 9, alcanzando los 1917 ppm, siendo este un valor muy alejado del límite de 30.000 ppm.

Teniendo ya los resultados de todas las variables importantes a tener en cuenta, se ha elaborado la siguiente tabla en la que se muestra si los sistemas han conseguido cumplir con los criterios de seguridad establecidos para cada escenario.

	Diametro (m)	**Criterio de Visibilidad**	**Criterio para CO**	**Criterio para CO_2**
Presurización 3000 m^3/h	0,5	YES	YES	YES
	1	YES	YES	YES
	1,5	YES	YES	YES
	0,5	YES	YES	YES
	1	YES	YES	YES

Presurización 9800 m³/h	1,5	YES	YES	YES
Ventilación natural	0,5	YES	YES	YES
	1	NO	YES	YES
	1,5	NO	YES	YES

Tabla 6. Cumplimiento de los criterios marcados por cada uno de los sistemas probados.

Conclusiones

El objetivo original de este estudio es responder a las necesidades expuestas en la norma NFPA 415 y proporcionar una solución al problema planteado: un sistema de protección que sea capaz de proteger de expulsión de gases y de humo de un incendio de combustible exterior. No sólo ha sido necesario pensar en un sistema que pudiera cumplir la tarea de la NFPA 415, sino también evaluar las capacidades y el rendimiento de este sistema ante este tipo de situación para mantener un entorno sostenible y confortable.

Para ello, se ha realizado un estudio exhaustivo de la situación. Una revisión literaria del tipo de incidentes que suelen producirse ha sido necesaria para identificar adecuadamente la situación. Por lo tanto, se ha realizado un análisis adecuado de los incendios tipo "pool fire" y su comportamiento, para definir con exactitud el tipo de situación para la que el sistema de protección debe ser eficaz. Gracias a este análisis, se ha creado un modelo para probar los sistemas de protección seleccionados (ventilación natural y presurización para 3000 m^3/h y 9800 m^3/h) y evaluar con confianza su rendimiento para tres situaciones diferentes de incendios.

Tras evaluar los resultados obtenidos, se puede afirmar con seguridad que la ventilación natural no es una opción válida al no mantener suficiente visibilidad. Al contrario, el sistema de presurización funcionó adecuadamente, logrando cumplir todos los criterios de seguridad para los dos caudales de aire probados. Este sistema consiguió incluso cumplir los criterios para un diámetro de 1,5 m. No obstante, este sistema parecía tener algunos problemas para cumplir con los criterios de confort, concretamente con un caudal de aire de 9800 m^3/h. Debido a la pequeña salida del HVAC, el flujo se acelera lo suficiente como para alcanzar velocidades seis veces superiores al límite de confort. No obstante, como el sistema ha sido capaz de cumplir con todos los criterios de seguridad con un caudal de 3000 m^3/h, se recomienda aquí emplear este sistema de presurización con este caudal de aire, ya que será capaz de mantener un ambiente seguro a la par que asegurando el confort de los pasajeros.

Por último, es importante señalar que este sistema de presurización debe depender de un buen sistema de activación. Como se ha revisado anteriormente, el sistema de activación utilizado en este estudio fue demasiado lento para poder mantener un ambiente sostenible en todo momento. Así, se recomiende la realización de un estudio para evaluar la mejor forma de activar el sistema de protección.

Referencias

[1] National Fire Protection Association, Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways, NFPA 415, 2022.

[2] Joshua D. Swann, Joseph L. Scheffey, Hughes Associates, Fire Protection Research Foundation, Aircraft Loading Walkways – Literature and Information Review, May 2014.

[3] American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), ANSI/ASHRAE 55-2017 – "Thermal Environmental Conditions for Human Occupancy", 2017.

[4] International Organization for Standardization (ISO), ISO 7730:2005: Ergonomics of the thermal environment, 2005.

[5] American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), Handbook of Smoke Control Engineering, 2007.

[6] Serban C. Moldoveanu, Pyrolysis of Organic Molecules: Applications to Health and Environmental Issues, 2019.

[7] M. Muñoz, J. Arnaldos, J. Casal, E. Planas, Analysis of the geometric and radiative characteristics.

Analysis of a pressurization system for airport's passenger walkways

Introduction

The National Fire Protection Association (NFPA), is an American entity in charge of developing technical codes and regulations for prevention and protection against fires. Through their codes, they are able to develop and implement effective measures to ensure the safety of people and property in a variety of settings, facilities and buildings.

More specifically, the NFPA has developed a specific regulation for airport terminal buildings, refueling ramps and boarding bridges: the NFPA 415 [1]. Thus, NFPA is able to propose a whole range of measures and strategies for the prevention and mitigation of fire-related risks and damages in the airport environment. The creation of a particular code for this area is of particular importance for two main reasons. Firstly, it is necessary to emphasize the importance of airports on a logistical and economic level. These infrastructures are crucial to a country for the development of various sectors such as trade, tourism and industry. Therefore, a serious incident in this type of infrastructures can have a very wide impact, in many areas and in a very lasting way that could have serious consequences for a country. In addition, airports are particularly sensitive to incidents. They are very busy places, with very complex and specific machinery. Historically, the criticality of safety and compliance in this area has been illustrated by major aviation disasters. For these reasons, the NFPA has decided to create a standard especially for airports.

In the most recent versions of NFPA 415, there is a section that mandates the presence of a pressurization systems on boarding bridges to protect indoor air quality from smoke in the event of an external fire. However, the lack of information and literature related to pressurization systems in boarding bridges and their performance is shocking, for a sector as rigorous and vulnerable as airports. As a result of this lack of information for such an important technical obligation, the motivation of this work arises. The main objective of this work is to respond to NFPA 415 and to analyze the compliance of a pressurization system with the objectives set by the standard, namely, to maintain a sustainable and comfortable environment for humans inside the jet bridge in case of external fire.

Methodology

The methodology chosen to approach this study is mainly divided into three parts: research and literature review, design and characterization of pressurization systems and boarding bridges, and finally modeling and simulation.

1. *Research and literature review.*

In order to be able to respond effectively to the NFPA 415 standard needs, it is necessary to have an adequate knowledge of the situations for which the pressurization system must protect indoor air quality. Thus, it is necessary to research the history of fire-related incidents at airports in order to investigate any information that may allow to define and characterize precisely for which context the system should operate.

As such, "Aircraft Loading Walkways - Literature and Information Review" , a document from The Fire Protection Research Foundations [2], has provided meaningful insight in this matter. It is a document which compiles descriptions and information regarding a series of incidents and accidents at airports involving fires. Thanks to this document, it has been possible to extract information, thus gaining a better understanding of the type of events and incidents common at airports. From this information, it has been possible to conclude that the main cause of fire-related incidents with 40%, according to the cases reviewed at airports, are pool fires, as a result of fuel spills. Also noteworthy are fires caused by electrical faults, representing 26.67 % of the total. However, in order not to overextend the scope of the work, these types of cases have not been studied, leaving them for future improvements.

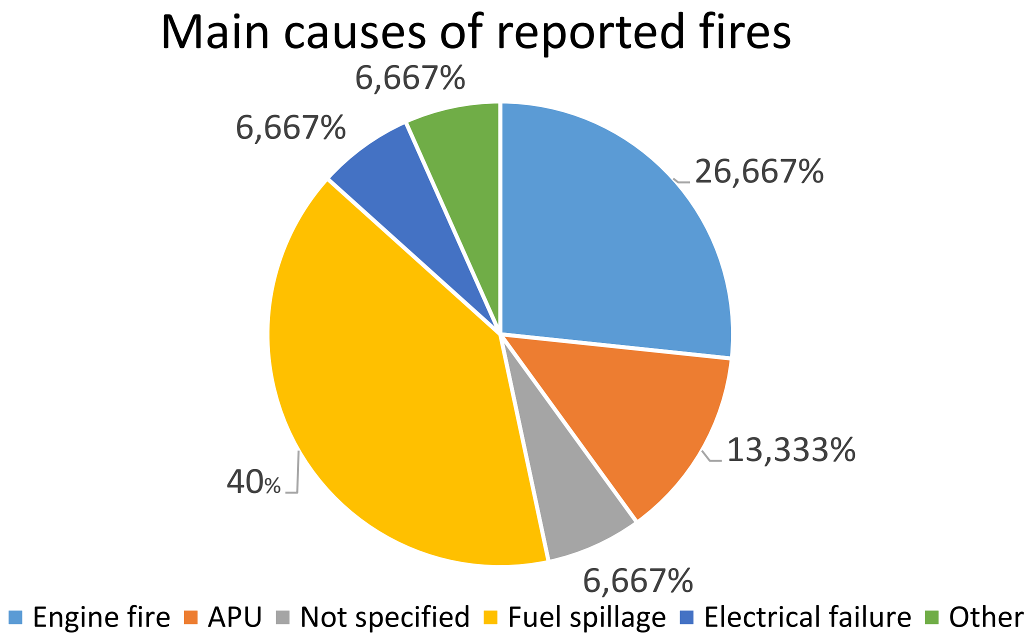

Fig.1. Main causes of fires in airports.

2. Design and characterization of pressurization systems and jet bridges.

Once the type of incident for which the pressurization system must protect has been defined, it is also important to understand the important parameters of the system and the loading walkway, that can impact both the design and performance of the system.

The first fundamental factor for a pressurization system is the flow rate used. Varying the flow rate of the system means higher internal pressure and therefore greater effectiveness in keeping toxic fumes and gases out of the boarding bridge. However, the flow rate has many other implications, since a different flow rate can result in different temperatures or greater or lesser comfort. In addition to the fact that the higher the flow rate, the more effective it should be in protecting against fumes, it also means higher consumption and lower savings. Thus, it is crucial to evaluate the flow rate used to protect the air in the walkway, while trying to reduce consumption.

In addition, human comfort is also important as it is one of the objectives of the project. One of the factors to be taken into account to evaluate comfort, is the air velocity. As stated in ANSI/ASHRAE Standard 55-2017 [3], the maximum velocity to ensure human comfort indoors is 0.5 m/s. In turn, as stipulated in ISO 7730 [4], the optimal velocities for human comfort are between 0.15 and 0.25 m/s. Thus, it was decided to test pressurization systems involving air velocities between 0.15 and 0.5 m/s, in order to ensure comfort while trying to maintain optimal air quality. To calculate flow from velocity, the following formula was used:

$$Q = w \cdot h \cdot v$$

Where Q is the flow rate, w and h are the inner width and height of the walkway and v is the air velocity. Thus, a flow rate of 3000 m3/h for a velocity of 0.15 m/s and a flow rate of 9800 m3/h for a velocity of 0.5 m/s have been obtained. Hence, the pressurization system will be tested for the whole range of speeds suitable to maintain a good level of passenger comfort.

In addition, the estimation of the leakage area of the boarding bridge is also of particular importance. On the one hand, it is through these leaks that smoke and external gases can more easily enter the jet bridge. Also, leaks of this type represent pressure losses ofor pressurization system. Pressure drops imply progressive pressure loss along the walkway. This is why it is particularly important to estimate them in order to be able to maintain a positive pressure until the end of the tunnel. In order to estimate them, "Handbook of Smoke

Control Engineering" [5] has been used, as it provides tables from which the following leakage areas have been obtained:

· External walls (Tunnel): 1,7·10-4 m^2/m^2

· Doble door and walkway: 0,0781 m^2

· Boarding door: 1,2·10-3 m^2/m^2

3. Model and simulation.

Once the type of fire and the key variables such as the system flow rate and the leakage areas of the walkway have been determined, the model to be used for the simulations has been developed.

This model was created through the Fire Dynamics Simulator (FDS) software. FDS is a computational fluid dynamics (CFD) software specialized in fire dynamics for different conditions and environments. In addition to using fluid dynamics or heat transfer equations like other CFD software, FDS additionally employs other models that allow users to predict fire behavior and complex dynamics such as smoke movement or flame spread. By simulating complex fire scenarios and modeling the behavior between fire, airflow and structures, FDS has become a widely used software for analyzing the design of fire protection plans and developing effective safety strategies.

In order to effectively model the scenario in FDS, certain simplifications and assumptions had to be made beforehand. This has been the case for the fuel introduced to the model. The most common fuel in commercial aviation is kerosene, mainly Jet A and A1. However, in this study, for the sake of simplicity, not all components will be taken into account and a simplified fuel will be used. According to S. C. Moldoveanu, 2019 [6], n-dodecane is one of the main components of kerosene and jet fuels. The pyrolysis of dodecane has been commonly used to understand the behavior of jet fuels. As such, for the simulated model , the fuel used will consist of n-dodecane.

In addition, an assumption also had to be made regarding the size of the fire pool. It is estimated that the system studied should protect in situations in which the structural safety of the walkway is not at risk, i.e. without the walkway being engulfed in the flames. Therefore, it has been estimated that the maximum diameter of the fire for which simulations will be carried out will be the one for which the flame height reaches the footbridge. A diameter of 1.45 m has been obtained, which was rounded to 1.5 m. Therefore, simulations will be performed for diameters such as 0.5, 1 and 1.5 m. The simulated scenarios are summarized in the following table.

Scenario	Smoke Control System	Pool Diameter
1	Pressurization (3000 m^3/h for 0,15 m/s)	0,5 m
2	Pressurization (9800 m^3/h for 0,5 m/s)	0,5 m
3	Natural ventilation	0,5 m
4	Pressurization (3000 m^3/h for 0,15 m/s)	1 m
5	Pressurization (9800 m^3/h for 0,5 m/s)	1 m
6	Natural ventilation	1 m
7	Pressurization (3000 m^3/h for 0,15 m/s)	1,5 m
8	Pressurization (9800 m^3/h for 0,5 m/s)	1,5 m
9	Natural ventilation	1,5 m

Table.1. Selected scenarios.

The next step for the actual development of the model was modeling the geometry. For this, the dimensions of the ThyssenKrupp TB 45/26.5-2 walkway model were roughly followed. It is made up of 15 sections, each 3 m long, each of which is arranged in a staircase configuration, with 0.25 m of step between each one. The section has an inner width and height of 2 and 2.5 m respectively. The exterior width and height are 2.5 and 3 m respectively. In addition, the entrance to the walkway from the airport (rotunda) and the entrance to the aircraft have also been modeled.

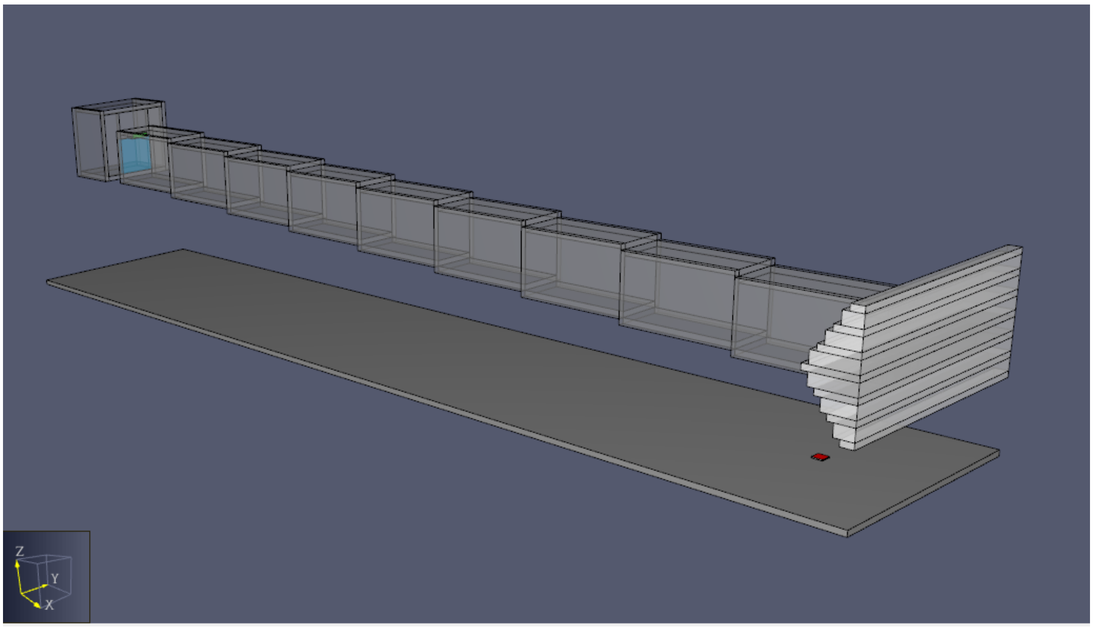

Fig.2. Modelo 3D de la pasarela.

Important devices have also been introduced such as:

- 15 smoke detectors spaced 3 m apart, in accordance with the standard.

- An HVAC at the entrance of the walkway (airport side) whose activation is given when at least two detectors are triggered.

- In the case of natural ventilation, two ceiling vents in the ceiling of the tunnel, in the central sections.

Also, the definition of boundary conditions is of particular importance for the model and the simulation. These are indispensable to define the flow of air, gases and heat transfer and thus, to determine the thermal and fluid behavior. In this case, the boundary conditions applied are:

- Air flow rate of the HVAC, it has already been defined for each scenario.

- No-slip condition on all solid surfaces (floor, walkway, airplane, etc).

- Open vent condition, which allows air to enter and exit the control volume.

- Mass loss rate, being the rate at which the fuel burns.

Therefore, it is necessary to estimate this mass loss in order to completely define the boundary conditions. For this purpose, the equations described in M. Muñoz et.al 2004 [7] have been used, which provide a method for its calculation in the case of gasoline. It has been considered appropriate to approximate it to gasoline due to its similar behavior:

$$\dot{m}'' = \dot{m}''_{\infty}(1 - e^{-k'D})$$

$\dot{m}''$ *being the mass loss rate* $(kg\ s^{-1}\ m^{-2})$.

$\dot{m}''_{\infty}$ *being the maximum mass loss rate* $(kg\ s^{-1}\ m^{-2})$, 0,083 *for gasoline*.

k' *being a constant parameter* (m^{-1}), 1,173 for gasoline.

D *being the pool fire diameter* (m).

Finally, in order to obtain a valid model, it is important to develop a mesh of sufficient quality. Furthermore, depending on the zone, it is important to control its size in order to have smaller elements in the most critical zones for higher accuracy and, likewise, larger elements in the non-critical zones for lower computational weight. Therefore, three meshes have been generated for three different zones. These three have been validated through a mesh alignment test. The important information of these three meshes is summarized in the following table:

Malla	Nº de elementos	Dimensiones de los elementos	Location
1	280.000	0,05x0,05x0,05 m	0,5 m layer above ground and around pool fire.
2	42.560	0,25x0,25x0,25 m	Above mesh 1, heights between 0,5 and 10 n
3	275.200	0,25x0,25x0,25 m	Rest of domain
TOTAL	597.760		

Table 2. Main mesh parameters.

Results

Before starting with the analysis of the results, it is important to define the criteria used for the validation of the protection systems. These criteria are based on those stipulated in NFPA 92 [8]. They are divided into two parts:

- Criteria for toxic gases. The objective of this criterion is to ensure that CO and CO2 levels do not pose a threat to human health. In the case of CO, the fractional effective dose of CO in each case shall be calculated and shall not exceed the values given in the following table.

Tiempo (min)	Limite		
	AEGL2	0.3	0.5
4	-	1706	2844
6	-	1138	1896
10	420	683	1138
15	-	455	758
30	150	228	379
60	83	114	190
240	33	28	47

Table 3. Limit for CO's fractional effective dose.

AEGL2, 0.3 and 0.5 are different criteria, in this case the 0.3 criterion will be used as it is the most commonly used. Thus, the fractional dose should not exceed 1706. In the case of CO2 the validation criterion is not to exceed the level of 30,000 ppm.

- Visibility criterion: the visibility should not fall below the 10 m limit.

As for the results, they have been separated into visibility, air speed, CO level and CO2 level. As for the visibility, it can be seen in the following figure how the visibility is lower than 10 m as soon as the diameter is higher than 0.5 m, before the ventilation system comes into action.

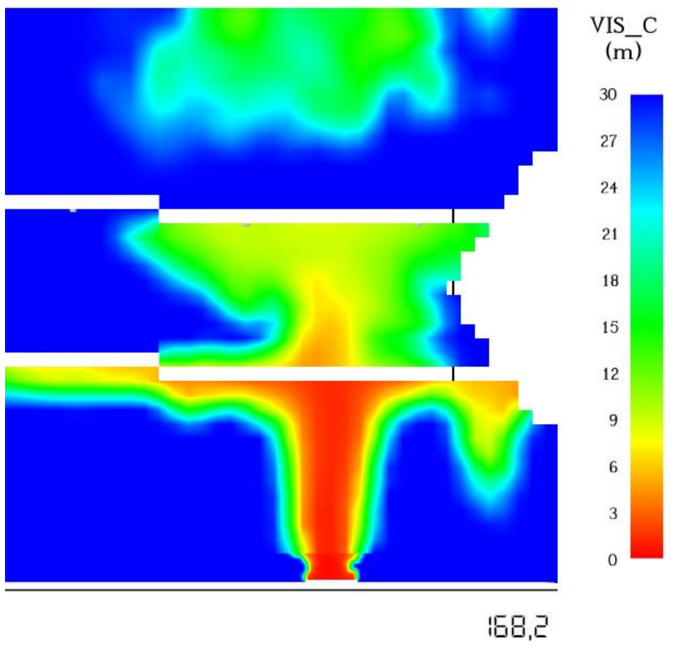

Fig.3. Contornos de visibilidad previos a la activación del sistema de presurización.

However, the improvement in visibility is remarkable once the pressurization system comes into action, achieving, even for diameters of 1.5 m, sufficient visibility with respect to the previously described criterion. however, this is not the case for natural ventilation.

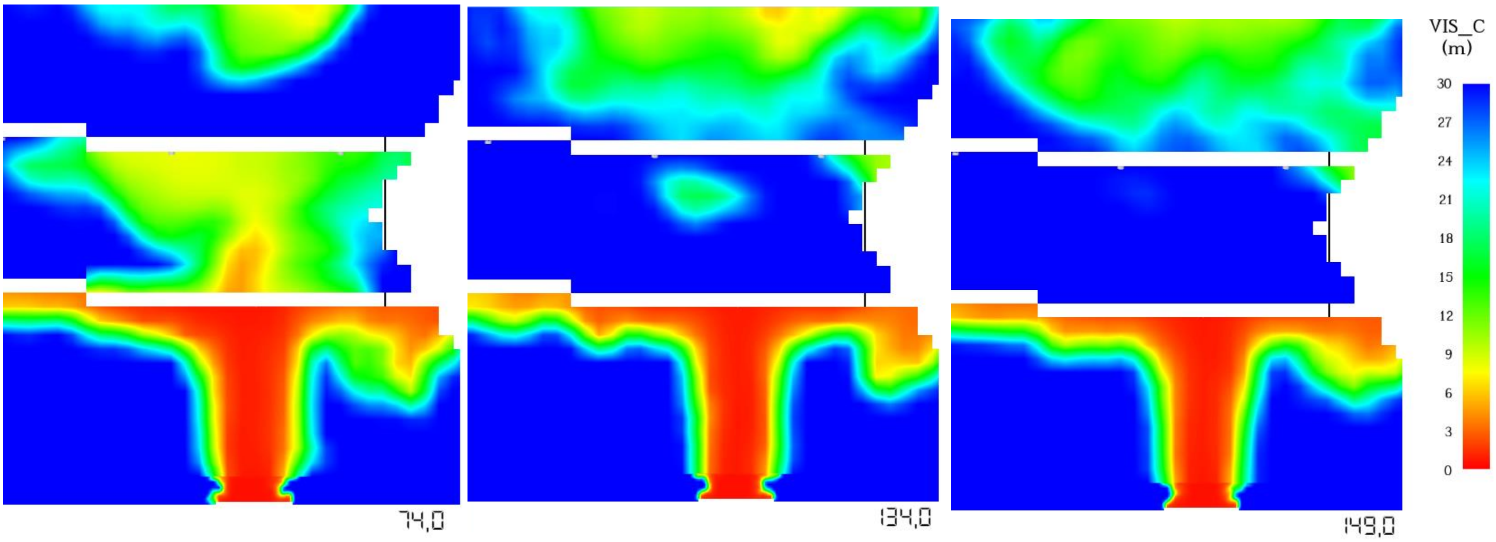

Fig.4. Visibility contours for scenario 8, at t=74, 134 and 149 s.

However, this is not the case for natural ventilation. The natural ventilation system is only able to maintain a visibility of more than 10 m in the case of 0.5 m diameter, but it is not effective for both 1 m and 1.5 m diameters.

In addition, air speed is important. High velocities imply greater discomfort for passengers and since one of the main objectives of the system is to maintain a comfortable environment, the velocity must be controlled. In this sense, the natural ventilation system complies, since it has velocities significantly lower than 1.5 m/s. For the pressurization system with a flow rate of 3000 m3/h, velocities close to the limit are reached. However, the area where these velocities occur is a reduced area near the air conditioner outlet. This result is normal since the outlet section is reduced, thus accelerating the air. This effect is greater for a flow rate of 9800 m3/h, where the air velocities are problematic, reaching at several points almost 3 m/s, six times the limit for human comfort.

Regarding the results related to visibility, they are summarized in the following table

		Previo a la activación		Despúes de la activación	
		Maxima perdida de visibilidad media (%/m)	Visibilidad minima (m)	Maxima perdida de visibilidad media (%/m)	Visibilidad minima (m)
Escenario	1	5,56	25,01	11,84	19,35
	2	5,712	24,86	11,222	19,9
	3	4,496	25,953	17,574	14,183
	4	27,096	5,614	16,65	15,02
	5	24,89	7,601	7,4	24,34
	6	34,307	0	38,244	0
	7	27,455	5,29	8,564	22,29
	8	27,608	5,153	0,123	29,89
	9	36,902	0	44,28	0

Table 4. Minimum visibility for each scenario, before and after activation.

The results are separated in two parts, on the one hand, the data prior to the activation of the natural ventilation and pressurization systems and on the other hand, the data after the activation of the natural ventilation and pressurization systems.

For the 0.5 m diameter cases, it can be seen how sufficient visibility is maintained throughout the simulation. This is not the case for the rest of the scenarios. It can be observed that for the 1 and 1.5 m diameters, the visibility criterion is infringed since it drops below 10 m. Despite this drop in visibility, it can be seen how the pressurization system is able to change the situation and recover visibility levels above 10 m for both scenarios, both with a flow rate of 3000 m3/h and 9800 m3/h. This validates the effectiveness of this system in maintaining safe visibility in case of external fire. However, the same is not true for the natural ventilation system. It is unable to maintain good visibility, even reaching zero visibility in cases 6 and 9, thus being discarded as a valid option to protect the walkway in case of fire.

Finally, the data related to the level of toxic gases remain to be analyzed. In the case of carbon monoxide, the following table has been prepared. This table shows the fractional dose obtained together with its confidence interval.

Scenario	1	2	3	4	5	6	7	8	9
FED_{CO} obtained	0,0103	$5,79 \cdot 10^{-3}$	0,0569	0,0204	$8,49 \cdot 10^{-3}$	0,192	0,0330	$8,33 \cdot 10^{-3}$	0,253

FED_{CO} bracket	[6,70·10^{-3}; 1,39·10^{-2}]	[3,77·10^{-3}; 9,56·10^{-3}]	[3,70·10^{-2}; 7,68·10^{-2}]	[1,33·10^{-2}; 2,75·10^{-2}]	[5,52·10^{-3}; 1,15·10^{-2}]	[0,125; 0,317]	[2,15·10^{-2}; 5,45·10^{-2}]	[5,41·10^{-3}; 1,12·10^{-2}]	[0,164; 0,341]

Table 5. Effective fractional doce of CO for each scenario.

All the results are far from the limit value of 1706, thus affirming the effectiveness of the systems in maintaining a low CO level. The same is true for CO2 levels. The maximum concentration of this gas obtained is in scenario 9, reaching 1917 ppm, a value far from the limit of 30,000 ppm.

With all the results having been taken into account, the following table has been drawn up to show whether the systems have managed to comply with the safety criteria established for each scenario.

	Diametro (m)	**Criterio de Visibilidad**	**Criterio para CO**	**Criterio para CO_2**
Presurización 3000 m^3/h	0,5	YES	YES	YES
	1	YES	YES	YES
	1,5	YES	YES	YES
Presurización 9800 m^3/h	0,5	YES	YES	YES
	1	YES	YES	YES
	1,5	YES	YES	YES
Ventilación natural	0,5	YES	YES	YES
	1	NO	YES	YES
	1,5	NO	YES	YES

Table 6.Criterion approval for each protection system.

Conclusions

The original objective of this study is to respond to the needs laid out in NFPA 415 [1] and provide a solution to the issue at hand: a protection system that will be able to protect passengers during an egress situation from the fumes and smoke from an outside fuel fire. Not only, was it necessary to think about system that could accomplish the task of NFPA 415 [1], but also to assess the capabilities and performance in this type of situation to maintain a tenable and comfortable environment.

As such, a thorough study of the situation has been performed. A review of the type of incidents that usually occurred has been necessary to identify properly the situation, to focus on pool fuel fires. Hence, a proper analysis of pool fires and their behavior was executed, along with the identification and analysis that could define with accuracy the type of situation for which the protection system had to be effective. Thanks to this analysis, a model could be created in order to test the selected protection systems (natural ventilation and pressurization for 3000 m^3/h and 9800 m^3/h) and assess with confidence their performance for three different pool fires situation.

After assessing the results obtained, it can be confidently stated that natural ventilation is not an option. It could have been the most optimal solution due to its low cost, maintenance, and consumption. Nonetheless, it could not keep up with one of the three crucial tenability criteria, as for any pool diameter superior to 0,5 m tested, it was able to maintain a visibility of at least 10 m. Furthermore, visibility is key as a low visibility will lead to slower evacuation and as such, more exposure to danger and the other two tenability criteria, CO, and CO_2 exposure.

On the contrary, a pressurization system performed adequately, managing to comply to all tenability criteria for both of the air flows tested, 3000 and 9800 m^3/h. This system even managed to comply with the criteria for the 1,5 m diameter pool, which represents a situation in which structural integrity is at risk due to high exterior temperatures and for which a system of this sort is not expected to perform. Nonetheless, this system appeared to have some issue to comply to comfort criteria, specifically with an air flow of 9800 m^3/h. Due to the small HVAC outlet, flow was accelerated enough to reach velocities six times faster than the comfort limit. Nonetheless, as the system was able to perform with only a 3000 m^3/h, it is recommended here to employ a pressurization system with this air flow, as it will be able to maintain a tenable environment, as well as comfort and be more economical than one with a higher air flow.

Finally, it is important to note that this pressurization system must be reliant on a good and measured activation system. As reviewed previously, the activation system used in this study was too slow to be able to maintain a tenable environment at all times. Hence, it is recommended that a study is done in order to assess the best way to active the protection system.

References

[1] National Fire Protection Association, Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways, NFPA 415, 2022.

[2] Joshua D. Swann, Joseph L. Scheffey, Hughes Associates, Fire Protection Research Foundation, Aircraft Loading Walkways – Literature and Information Review, May 2014.

[3] American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), ANSI/ASHRAE 55-2017 – "Thermal Environmental Conditions for Human Occupancy", 2017.

[4] International Organization for Standardization (ISO), ISO 7730:2005: Ergonomics of the thermal environment, 2005.

[5] American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), Handbook of Smoke Control Engineering, 2007.

[6] Serban C. Moldoveanu, Pyrolysis of Organic Molecules: Applications to Health and Environmental Issues, 2019.

[7] M. Muñoz, J. Arnaldos, J. Casal, E. Planas, Analysis of the geometric and radiative characteristics.

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TRABAJO FIN DE MASTER

Analysis of a pressurization system for airport's passenger walkways

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Chapter 1: Introduction

1.1 Introduction

The National Fire Protection Association (NFPA) is a US association that sets international standards regarding both fire prevention and protection standards. Through their codes and standards, the NFPA is able to set the measures necessary to ensure safety in a variety of fields and installations. Particularly, NFPA 415 is the code defining the requirements that airports have to meet to be safely protected from any type of fire incidents. Furthermore, Airports are singularly vulnerable infrastructures to fires incidents. On the one hand, airports can have a very high risk of an important fire incident as the number of possible sources of fire is high, spanning from engines failures or any type of mechanical machine issue, a variety of electrical fires or especially fuel fires. Large amount of very flammable jet fuel is present in airports, representing an important threat to safety. On the other hand, a fire incident can be catastrophic in an airport as these are strategically important structures, which also hold a high number of people that could turn into potential victims.

As such, NFPA 415 is an especially important code, defining a wide variety of strict measures to ensure fire safety, as fire protection in airports is of the upmost importance. One of the situations NFPA 415 aims to ensure is the safe evacuation of passengers from airplanes when a fire is present. Various methods are employed when it comes to egress or ingress passengers out or in airplanes, such as passenger walkways. Hence, protection methods for loading walkways are a key part in NFPA 415, to ensure safe evacuation of airplanes. One of the measures adopted in the most recent version of the code is the introduction of pressurization systems in walkways to guarantee no smoke will entry the walkway during evacuation as this could be a crucial threat [1].

Fig 1.1. Loading walkway

Surprisingly, a pressurization system does not seem yet to exist for loading walkways as the regulations is new. Nevertheless, as the NFPA now mandates its use [1], it is necessary to develop it.

Nevertheless, it is not an easy system to design due to a variety of factors. For example, walkways are usually quite small and crowded places in which the accommodation of big ventilation systems is difficult. Additionally, walkways are far from airtight due to their big leak area hence, increasing the difficulty. Other factors will also need to be taken into account considerations like ambient conditions etc.

To pressurize a space, it is necessary to maintain a positive pressure inside it, this can be made for example by “pushing” the air outwards, this way the inside air can stay clean of any dangerous smoke or fumes that may enter from the outside in case of a fire. Nevertheless, the design must take into account the type of fire, the geometry or ambient conditions to ensure that in an efficient manner, pressure is maintained in any type of conditions without disrupting the commodity for users.

As airports continue to expand and become increasingly crowded, the need to evaluate and analyze the performance of pressurization systems has never been more crucial. The safety of passengers in airports relies heavily on these systems, and a minor malfunction can have catastrophic consequences. Thus, it is vital to conduct a detailed analysis of pressurization systems in passenger walkways in airports, identifying the key factors that must be considered in designing and evaluating these systems. This analysis will provide valuable insights into the challenges and opportunities associated with these systems and inform future research and development efforts in this area.

1.2 State of the art

Regarding the state of the art, some key information can be found that will help to analyze the introduction of a pressurization system in jet bridges. As stated, no pressurization system exists at this present moment for loading walkways. No system has been introduced that is now able to maintain a positive pressure inside bridges, not to speak of a system that will maintain a sufficiently positive pressure in order to ensure that in any case fumes or smoke will enter the walkway.

Nevertheless, some systems already exist that could help open the way in this field. Some of these systems can serve as a starting point for designing an efficient and effective way of being in compliance with NFPA 415.

First, some jet bridges are already equipped with Environmental Control Systems (ECS). These ECSs usually consist of an air conditioning system (HVAC) that is able to maintain proper temperature and humidity, a ventilation system and a filtering system to avoid pollutants coming inside the bridge. Most of these ECS are built in-structure of jet bridges, during their initial construction but in some cases HVAC systems are retrograded in already existing walkways. For example, JetAire is a company that mounts these systems and that offers an interesting option to upgrade jet bridges and which strategy could be a valuable option regarding pressurization systems.

Fig 1.2. JetAire HVAC unit attached to a Jet bridge.

Even though pressurization systems have not been yet adapted to loading walkways, these are systems that have existed for a long time. The first practical use of a pressurization systems is dated in the early 19th century and since then, these have been greatly refined, improved and adapted for a variety of places and purposes.

Nowadays, we can find pressurization systems everywhere, ranging from aircraft cabins or submarines to greenhouses, hospital rooms or even computer server rooms. Of course, for the sake of this work, it will be necessary to study thoroughly pressurization systems, the variety of them, how they are applied and how they work. A good understanding of them will be crucial to achieve a good design of a pressurization system for loading walkways.

Nonetheless, as the amount of this systems and the number of different applications they have are substantial, there are systems that are applied for similar structures and applications. As such, the analysis of similar pressurization systems can be an important asset for the analysis and design of efficient and effective pressurization systems in jet bridges. Loading walkways have very particular features which make them singular when it comes to assessing the possibility of pressurization. Hence, it is necessary to look for systems which share these distinctive attributes. Primarily, these particularities are a thin and long geometry, large leak areas jet bridges have as they are far from being air tight, the need for a comfortable environment and the fact these can be crowded. There are not many examples of a system that perfectly matches the features of a walkway but there are various that can be quite similar. For example, the pressurization system of a subway train can be very interesting regarding this study. They share a long and thin geometry with walkways. They also share the need for a comfortable environment for people as both may be crowded. However, even if these are not airtight, they still have a lower leak area than jet bridges. Another interesting example is the system installed for warehouses, manufacturing facilities or greenhouses. Even if these do not share the walkways geometry, they do match the fact that they do have quite large leak areas and can also be crowded.

As such, even if there is an absence of pressurization systems for loading walkways in airports, there is an important amount of information regarding pressurization systems and ventilation. The state of the art on this matter is far from being irrelevant and it is a prime asset for this study. Hence, both the existing ventilation and HVAC systems existing in walkways and similar pressurization systems will be subject to an in depth analysis within the scope of this work.

1.3 Motivation

Air travel and transportation is one of the safest industries existing, as it has one of the lowest percentage of accidents and incidents, especially regarding fatal accidents or injuries. According to the International Air Transport Association (IATA), a total of 1,2 billion passengers traveled in 2019, with a total rate of 1,13 accidents per million flights [2]. These levels of safety in this industry are a direct result of the strict regulations imposed to every aspect of this industry. Through strict regulations, everything is controlled and supervised, every possible scenario is taken into account and all preventive measures are taken to avoid any situation that could lead to an accident or incident.

The carefulness with which these regulations are being created and implemented is not groundless. One the one hand, by the nature of the industry, any type of small issue or incident can very rapidly turn into a catastrophic accident with a boundless loss of life and capital, as already seen in the past. On the other hand, airports and air transportation are logistically and strategically of the upmost importance for countries, being crucial for commerce and the economy in general. Airports are key infrastructure for an important percentage of the economy and as such, they need to be protected to be able to keep on functioning normally.

As previously stated, NFPA 415 has stated the need for pressurization of jet bridges even though these do not currently exist. Of course, this contradiction is the first and most obvious motivation for this study: to ensure the regulation of NFPA 415 can be met. This new regulation represents an important challenge as developing and assessing the performance of a pressurization system for walkways is quite complex. Various aspects of loading bridges can be an obstacle to be able to protect them effectively against fumes and smoke, such as its very distinct geometry, or the fact that these are usually crowded even though they have little space. There is a clear lack of development of this issue in the industry even though the need is present. As such, the motivation for this work is the analysis of feasibility and performance of various pressurization or protection systems as a function of variables that can affect it such as geometry, leak area and fire source.

Nevertheless, the motivation in this study goes beyond this. Through this work, the intent is to help maintain the levels of safety that make air travel one of the safest industries in the world, ensuring that everything possible to avoid loss of life is done and to protect the key infrastructure that airports represent.

1.4 Objectives

The main objective is to respond to the need imposed by the new standard NFPA 415. As such, a feasible pressurization system comfortable for any passengers inside the walkway needs to be designed to prevent the smoke propagation under open fires that could occur on an airport runway. A pressurization system is not the only technical option available to respond to these needs. As such, various options will be studied, their ability to perform and protect from a fire and their suitability for the presence of passengers and their comfort. For example, natural ventilation system will also be examined as an alternate possibility. The performance of the system will be assessed as a function of many variables such as type of protection system, air flow, geometry, or size of fire.

1.5 Project methodology

The project will be divided in four main parts which include a literature review, design of pressurization systems in loading walkways, computational assessment of pressurization systems in loading walkways and conclusions:

1. Literature review: This part will consist in acquiring the knowledge necessary in all the areas this project contains. For once, we will search for data regarding statistics of fires in international airports in general, and more precisely in loading bridges. Also, it will be necessary to study the various types of fires that can occur in airports. Fires can have very different behaviors depending on the type of fuel, size, or conditions, which can cause different consequences and behave in very dissimilar ways. As such, a thorough research and analysis of these will be crucial for the well-being of this study.

2. Design of pressurization systems in loading walkways: Since the primary objective of this project is the design of a pressurization system for loading walkways, the understanding of pressurization systems is of the upmost importance. Hence, there will be a review and study of the basics of pressurization systems to acknowledge the way they work and important factors. Secondly, we will assess all the different variables that can directly impact a pressurization system in the case of loading walkways. Some of these variables are geometry and volume, leak areas, ambient conditions, or type of fire they are exposed to.

3. Computational assessment of pressurization systems in loading walkways: Once the necessary base of knowledge of pressurization systems and fire behaviors has been acquired, we will assess the behavior of these systems when exposed to the type of fires and conditions they can be exposed in airports. This process will be accomplished through CFD, for which it will first be necessary to learn to use Fire Dynamics Simulator (FDS), one of the most common software for CFD analysis applied to fire dynamics. Then, we will perform a series of simulations to assess the system performance. Finally, we will obtain the main results and the relations between performance and affecting variables.

4. Final report and conclusions: Finally, we will assess the results and draw the necessary conclusions from it.

1.6 Alignment with SDG's

In accordance with the UN line of action, this project will have to be in frame with the objectives set by the Sustainable Development Goals (SDG) [3]. As the world changes rapidly and demands new goals and compromises, all industries have to adapt in order to still be aligned with the news needs of the world, which are summarized in the SDG's .

Furthermore, the air transportation industry is one of the most important in the world but also one of which produces the most emissions to the atmosphere. As such, it is especially important that this project that regards this industry helps it transform it and shift towards the needs set in the SDG. Various of the 17 SDG's can be achieved within the scope of this particular project, some of which are:

2– Good health and well-being: This project is directly related to this goal. It not only intends to respond to the needs set in a specific regulation but rather respond to the reason why the regulation was set. From a more global perspective, this project aims at improving the safety of passengers in airports when traveling by preventing any type of fumes or smoke entering any airport’s loading bridges. Hence, this project will not only prevent serious injuries, but any type of health related issues caused by smoke.

9 – Industry, innovation, and infrastructure: As set by the UN, one of the SDG’s is “Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.” Airport’s being of the most important infrastructures, this project aims directly at this 9th SDG by improving its resilience and security.

Chapter 2: Literature review

2.1. Objectives of literature review

A thorough literature review is of the upmost importance in this study. To be able to meet the objectives properly, it is imperative that the necessary information is acknowledged regarding all the possible factors that could affect the pressurization of a jet bridge to avoid any outside fumes or smoke entering. As the primary objective of this study is the analysis of a pressurization system for jet bridges to avoid fumes coming in, there are four main areas that will need of a literature review to be able to define and understand correctly all the factors involved.

First, it will be necessary to understand for which type of situations pressurization systems are needed. As stated in NFPA 415, no smoke or fumes from an outside fire can enter the walkway and hence, this is the situation for which systems need to be analyzed. Hence, a description of the types of fires that can occur near walkways will be studied through the review of related reports and data. Not only the type of fire is to be determined, but also important parameters that will affect directly the simulation. For instance, it is important to define the distance between fire and walkway and size of the fire. The main objective of this study is to assess if a pressurization system will be able to permit a fume and smoke free egress for passengers through the walkway. As such, it is crucial to define precisely for which situations pressurization systems need to be studied: which type of fire, at which distance, what fuel and of which size.

2.2. Fire history review.

In this section, various incidents will be reviewed of fires near loading walkways. In general, by collecting a series of these incidents, a better and deeper understanding of the fire situations in which jet bridges can be affected will be acquired. These incidents mainly come from the document "Aircraft Loading Walkways – Literature and Information Review" of The Fire Protection Research Foundations, published in May 2014, [4]. In some cases, the presence of a loading walkway is not specified but some cases can still offer some information regarding the types of fires incidents that frequently occur.

The following events and incidents are comprised of primarily ramp fires or other situations in which an evacuation of the passengers was required. Most of the following happened at the gate and if not, near the gate. While these incidents are not necessarily related to loading walkways, they do provide examples of the types of fire incidents and factors that can influence the performance of a pressurization system, such as the one this work intends to analyze. The following history of fires and incidents provides examples of events that involved a fire or fuel spills associated:

· JetBlue Airways flight 1329 experienced a minor engine fire when taxiing its way to the gate at BWI Thurgood Marshall International Airport on November 21, 2012. The aircraft first continued to the gate where the fire was extinguished by fire crews. The aircraft was an Embraer E190, all passengers and crew members evacuated though the walkway with no injuries.

Fig 2.1. JetBlue Airways engine fire, November 2012.

· On April 20, 1998, a Boeing 727 of American Airlines had to be evacuated while at the gate at O'Hare international airport. An uncommanded evacuation occurred when the plane auxiliary power unit caught fire and the passengers saw the flames. Nevertheless, the evacuation did not occur though the walkway, passengers opened the over wing door, after which the attendant opened the rear airstairs. The crew managed to stop the evacuation and then was conducted mannerly through the airstairs. Three injuries were reported one of which was serious.

· October 29th, 2015, a Boing 767 from Dynamics International Airways caught fire while taxiing on its way to the runway at Fort Lauderdale-Hollywood international Airport. A fuel leak occurred, which ignited and prompted the evacuation through the ramps of the 101 passengers, of which 15 were injured. Reportedly, between 45 and 50 gallons of fuel were spilled.

Fig 2.2. Dynamics International Airway's B767 after the fire at Fort Lauderdale Airport

· On the 8th of March 1998, a DC-10 caught fire while taxiing at Manchester International Airport. On its way to the runway, pilots noticed a slight smell of gasoline and stopped at a holding point. Tower control informed of vapor coming from one of the engines. Due to a fuel leak, fire appeared and the crew proceeded to the evacuation of all passengers with only 2 minor injuries.

· On August 20, 2007, China Airlines flight 120 Captain was notified of an engine fire during its taxi to the parking location in Okinawa. All the 118 passengers evacuated though the deployed slides, but the aircraft was completely destroyed.

· British Airtours flight G-BGJL caught fire as a result of a failure in the left engine and the resulting fuel leak on August 22, 1985, at Manchester International Airport. During takeoff, the left engine failed with a clear noise forcing the crew to abort takeoff. At first, the crew believed a tire blew up but as fume began to enter the cabin, the captain ordered to evacuate the aircraft. The fire spread and even if 82 passengers managed to egress through the slides, 55 passengers died in the accident.

· A Boing 787 operated by Japan Airlines caught fire at Logan International Airport in Boston the 8th of January 2013. Luckily no one was inside the plane at the time of the incident. Ground crew reported the presence of dense white smoke and firefighter were quickly called. The issue was determined to be the batteries of the Auxiliary Power Unit, which leaked and caught fire.

·In Atlanta, on November 29, 2000, a DC-9 experienced smoke and fire in the cabin. The 97 occupants evacuated with only thirteen injuries. Electrical failures were noticed immediately upon take-off. The captain decided to return to the airport and upon landing, smoke was visible within the cabin. Evacuation took place on the ramp, immediately upon landing.

As seen by the Fire history review presented, it is evident that landside aircraft accidents happen, which result in the emergency evacuation of passengers and crew members. Some of the identified scenarios involve fuel spill fires and other threats at the airport terminal gate, indicating the involvement of loading walkways in emergency egress situations. The incident history indicates that people will use any means of egress to get away from the perceived danger during an emergency evacuation scenario, including evacuating down slides onto the ramp near the gate or on a ramp area/taxiway/runway and via the over wing exits. Despite the visible fire threat in some cases, passengers and crew members have successfully evacuated the aircraft through the walkway, or from aircraft exits if needed. Although in one of the presented incidents, passengers evacuated through unarmed emergency exit doors, the crew's procedure in response to fires is aligned with either slides or loading walkways.

2.3. Characterization of fires in airports.

An important variety of types of fire can occur near loading walkways that will have different behaviors and different smokes and fumes. According to the Fire Protection Research Foundation 2014 report "Aircraft Loading Walkways – Literature and information review" there is a great diversity regarding fire situations that can affect severely loading walkways and a safe evacuation through them. For instance, in the report, electrical fires from maintenance vehicles are cited, engine fires, power unit fires or jet spills fires. Of the many real case reported in the document, all vary in location or materials burnt, as such, influencing in notably different ways the evacuation of the jet bridge and the presence of smoke and fumes. Hence, for the sake of this study, not all situations will be considered as it would broaden too much the scope of it. Nevertheless, for a possible future study, the analysis of other situations and type of fires would be of interest.

With the base of 15 reported incidents available, the following graphics have been done to illustrate the situation regarding the causes of fire that need of an evacuation of the occupants:

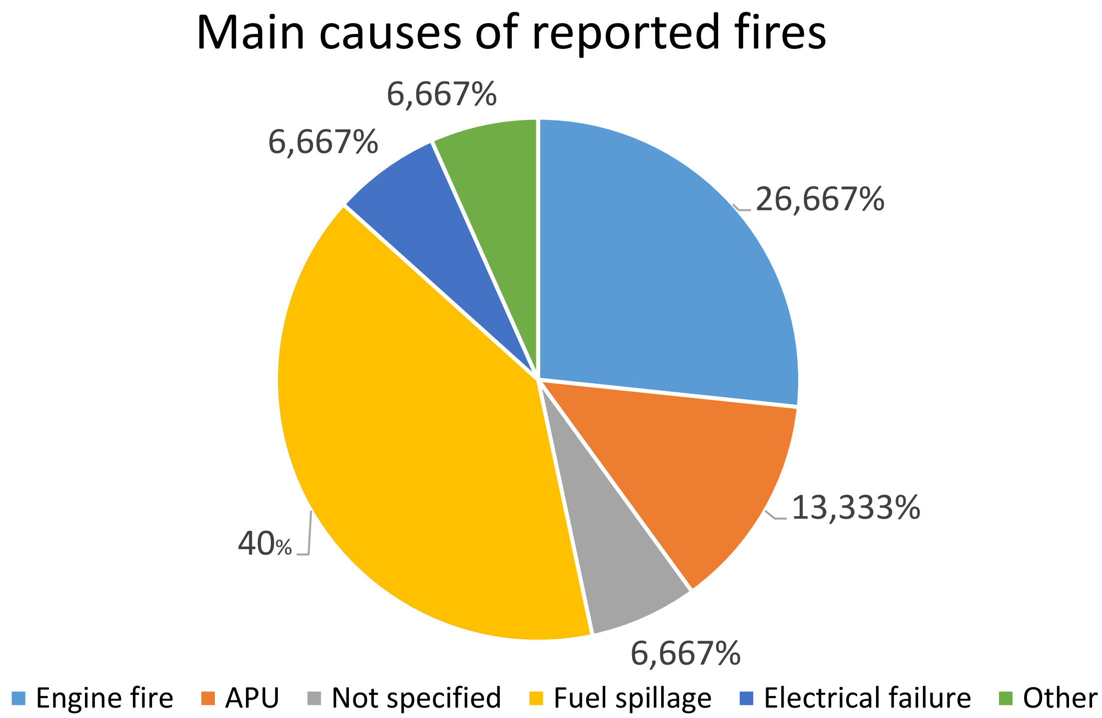
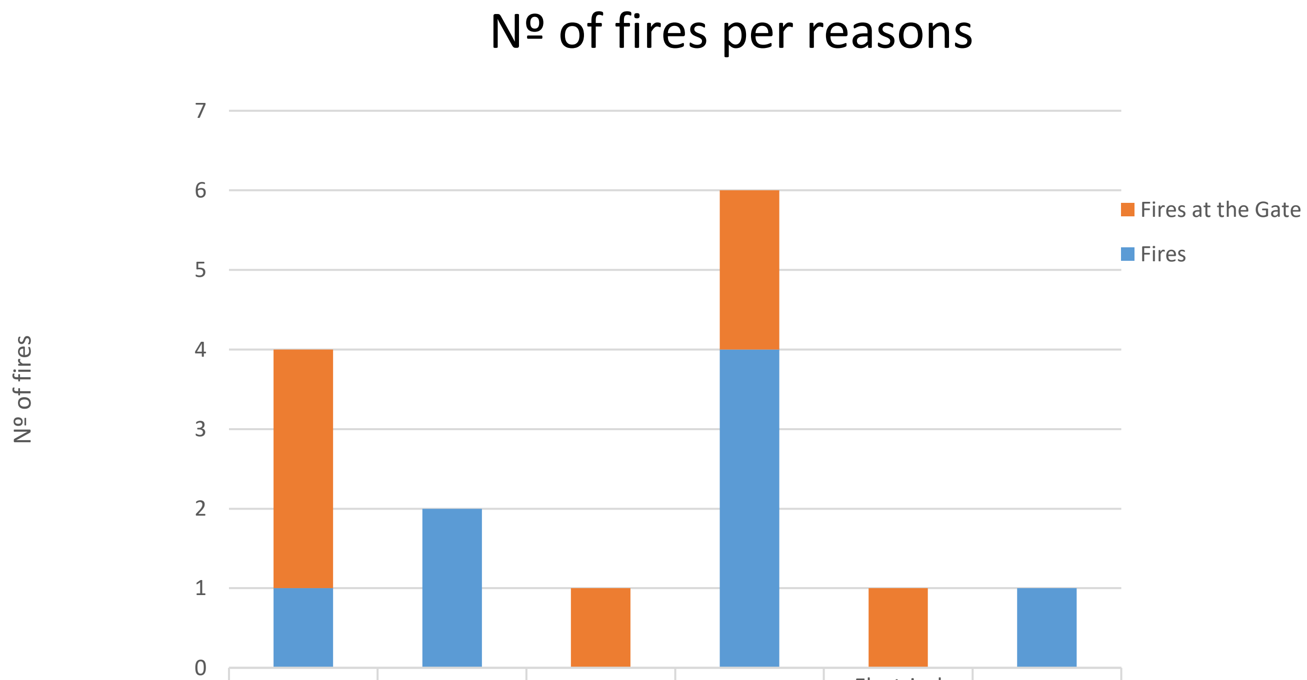


Fig 2.3. Percentages of each cause of fires of the reviewed fire incidents



	Engine fire	APU	Not specified	Fuel spillage	Electrical failure	Other
Fires at the Gate	3	0	1	2	1	0
Fires	1	2	0	4	0	1

Fig 2.4. Number of fires related to their cause and location at the gate.

As seen in the summarized information of the graphics, the main cause of the 15 reviewed fire incidents is jet fuel spills with up to 40 % of the fires. Of these 6 fires related to fuel spills, all needed the evacuation of the passengers and in 2 cases (33,33 %), the incident occurred at the gate. The information regarding if the fire occurred at the gate is particularly interesting as it is directly related to the presence of loading walkways. Other main types of fires are the ones related to engine fires which account to 26,667% of the incidents reviewed, followed by APU fires with 13,333% and finally electrical failures, unspecified fires and other ones with 6,667% each.

In order to narrow the scope of the project in a manageable manner, only one type of fire will be studied. According to the NFPA 415, the pressurization system is needed to restrict the entry of smoke from a free-burning jet fuel spill hence, the focus will be put on jet fuel pool fires. This goes in the same direction with the data compiled by the 15 incidents studied in which the main cause was fuel spills that represent pool fires.

Chapter 3: Design of pressurization or natural ventilation systems in loading walkways.

To create meaningful and precise simulation and validate the performance of the pressurization system, the main factors involved have to be identified and studied as a mean to evaluate, during the simulations, the value of the parameters involved such as airflow and others. For this, the NFPA has a its code NFPA 92 that establishes the requirements of smoke control systems such as the ones that will be assessed in this analysis. As stated in the article 1.2.1 of the document, the purpose of the standard 92 is [5]:

"The purpose of this standard shall be to establish requirements for smoke control systems to accomplish one or more of the following:

(1) Inhibit smoke from entering stairwells, means of egress, smoke refuge areas, elevator shafts, or similar areas.
(2) Maintain a tenable environment in smoke refuge areas and means of egress during the time required for evacuation.
(3) Inhibit the migration of smoke from the smoke zone.
(4) Provide conditions outside the smoke zone that enable emergency response personnel to conduct search and rescue operations and to locate and control the fire.
(5) Contribute to the protection of life and to the reduction of property loss."

In this case, the objectives will be to accomplish points (1), (2) and (5) of the article 1.2.1 of NFPA 92, as loading walkways represent an important mean of egress and securing this zone can contribute to the protection of life.

For once, a crucial factor to evaluate is the airflow provided by the pressurization system. Its ability to comply to the objectives set by NFPA 92 is directly related to the airflow introduced to the loading walkway. As the airflow increases, the pressure will increase, and the entry of smoke reduced. Hence, the simulations will be focused on finding the optimum airflow provided by the pressurization system to meet the NFPA 92 requirements.

Nevertheless, the airflow is restricted as it can cause an untenable environment for people inside the jet bridge: a higher airflow entails a higher air velocity which can be uncomfortable or even untenable for passengers. As set by ANSI/ASHRAE Standard 55-2017 [6], the maximum air velocity indoors for human comfort is 0,5 m/s. On the other hand, as ISO standard ISO 7730 [7] sets, the optimum air speeds for comfort are comprised between 0,15 and 0,25 m/s. As such, the range of values that will be between 0,15 and 0,5 m/s.

One of the main manufacturers of loading walkways is ThyssenKrupp, which also has the longest model available in the market. This model of loading walkway, the “TB 45/26.5-2”, will be the one used for the model required in the simulations. Longer jet bridges will incur in higher pressure losses along the length of the walkway and as such, will incur in a lower pressure at the end of the walkway. Hence, just where the fire will be place, the pressure will be lower and will not be able to protect as efficiently the passenger from the try of smoke. The analysis of a pressurization system for the TB 45/26.5-2 walkway is the more pessimistic scenario. As such, a good result for this model provides a higher level of trust for a pressurization system for protection from smoke against an exterior pool fire.

Fig 3.1. ThyssenKrupp’s TB 45/26.5-2 loading walkway.

To assess the airflows that will be evaluated for the pressurization system during the simulations, only the internal area of the walkway is necessary, as the air velocities (v) are already known. For the specified model, the internal tunnel has a width (w) of 1,49 m and a height (h) of 2,10 m. For generalization purposes, more standardized dimensions will be used, 1,8 m width and 3 m height. With the following formula, the airflow (Q) is determined:

$$Q = w \cdot h \cdot v$$

Hence, an air velocity of 0,15 m/s equals a rounded flow of 3000 m^3/h and an air velocity of 0,5 m/s equals an approximate flow of 9800 m^3/h.

Another important factor regarding loading walkway for elaboration of accurate simulations is the leak area. Through leak areas, pression is lost in walkway and as such, negatively impacts the performance of the pressurization system. Additionally, the smoke produced by the fire will enter the walkway through these leak areas. Consequently, it is important to determine the leak areas.

The following values have been estimated with the following tables [8], assuming an average leakage:

· Loading walkway external walls (Tunnel): 1,7·10-4 m^2/m^2

· Double door between the terminal and the walkway (Rotunda): 0,0781 m^2

· Loading walkway boarding gate (Cabin): 1,2·10-3 m^2/m^2

Construction Element	Leakage	Area Ratio[2] Leakage Area per Unit Wall Area		
		in^2/ft^2	ft^2/ft^2	m^2/m^2
Exterior building walls (includes construction crack and cracks around windows and doors)	Tight	$7,2x10^{-3}$	$5,0x10^{-5}$	$5,0x10^{-5}$
	Average	$2,5x10^{-2}$	$1,7x10^{-4}$	$1,7x10^{-4}$
	Loose	$5,0x10^{-2}$	$3,5x10^{-4}$	$3,5x10^{-4}$
	Very Loose	$1,7x10^{-1}$	$1,2x10^{-3}$	$1,2x10^{-3}$
Stairwells walls (includes construction cracks but not cracks around windows or doors)	Tight	$2,0x10^{-3}$	$1,4x10^{-5}$	$1,4x10^{-5}$
	Average	$1,6x10^{-2}$	$1,1x10^{-4}$	$1,1x10^{-4}$
	Loose	$5,0x10^{-2}$	$3,5x10^{-4}$	$3,5x10^{-4}$
Elevator shaft walls (includes construction cracks but not cracks around doors)	Tight	$2,6x10^{-2}$	$1,8x10^{-4}$	$1,8x10^{-4}$
	Average	$1,2x10^{-1}$	$8,4x10^{-4}$	$8,4x10^{-4}$
	Loose	$2,6x10^{-1}$	$1,8x10^{-3}$	$1,8x10^{-3}$
Floors[3] (includes construction cracks and gaps around penetrations)	Tight[4]	$9,5x10^{-4}$	$6,6x10^{-6}$	$6,6x10^{-6}$
	Average	$7,5x10^{-3}$	$5,2x10^{-5}$	$5,2x10^{-5}$
	Loose[4]	$2,4x10^{-2}$	$1,7x10^{-4}$	$1,7x10^{-4}$

[1]The data in this table are for use with orifice equation. Flow area ratios for flow coefficient C = 0,65 at 0,3 in H_20 (75Pa).
[2]Values pf area ratios based on pressurizaiton measurements in buildings by Tamura and Wilson (1966), Tamura and Shaw (1976a; 1976b; 1978) and Shaw, Reardon and Cheung (1993).
[3]Floor leakage does not account for gaps that can be between a floor and a curtain wall.
[4]Values extrapolated from the average floor tightness based on range of thightness of other constructions components.

Table 3.1. Flow areas of walls and floors.

Gap Thickness at Bottom		Gap Thickness at Top and Sides		Gap Thickness at Center		Flow Area	
in.	mm	in.	mm	in.	mm	ft^2	m^2
0,25	6,36	0,02	0,508	0,08	2,032	0,200	0,0185
0,25	6,36	0,02	0,508	0,12	3,048	0,234	0,0217
0,25	6,36	0,02	0,508	0,16	4,064	0,267	0,0248
0,25	6,36	0,08	2,032	0,08	2,032	0,305	0,0284
0,25	6,36	0,08	2,032	0,12	3,048	0,340	0,0316
0,25	6,36	0,08	2,032	0,16	4,064	0,373	0,0346
0,25	6,36	0,12	3,048	0,08	2,032	0,391	0,0363
0,25	6,36	0,12	3,048	0,12	3,048	0,426	0,0396
0,25	6,36	0,12	3,048	0,16	4,064	0,459	0,0426
0,25	6,36	0,16	4,064	0,08	2,032	0,472	0,0438
0,25	6,36	0,16	4,064	0,12	3,048	0,506	0,0471
0,25	6,36	0,16	4,064	0,16	4,064	0,540	0,0501
0,5	12,70	0,02	0,508	0,08	2,032	0,350	0,0325
0,5	12,70	0,02	0,508	0,12	3,048	0,385	0,0358
0,5	12,70	0,02	0,508	0,16	4,064	0,418	0,0388
0,5	12,70	0,08	2,032	0,08	2,032	0,456	0,0424
0,5	12,70	0,08	2,032	0,12	3,048	0,491	0,0456
0,5	12,70	0,08	2,032	0,16	4,064	0,524	0,0487
0,5	12,70	0,12	3,048	0,08	2,032	0,542	0,0504
0,5	12,70	0,12	3,048	0,12	3,048	0,577	0,0536
0,5	12,70	0,12	3,048	0,16	4,064	0,610	0,0566
0,5	12,70	0,16	4,064	0,08	2,032	0,623	0,0579
0,5	12,70	0,16	4,064	0,12	3,048	0,657	0,0611
0,5	12,70	0,16	4,064	0,16	4,064	0,690	0,0641
0,75	19,05	0,02	0,508	0,08	2,032	0,501	0,0466
0,75	19,05	0,02	0,508	0,12	3,048	0,536	0,0498
0,75	19,05	0,02	0,508	0,16	4,064	0,569	0,0528
0,75	19,05	0,08	2,032	0,08	2,032	0,607	0,0564
0,75	19,05	0,08	2,032	0,12	3,048	0,641	0,0596
0,75	19,05	0,08	2,032	0,16	4,064	0,675	0,0627
0,75	19,05	0,12	3,048	0,08	2,032	0,693	0,0644
0,75	19,05	0,12	3,048	0,12	3,048	0,727	0,0676
0,75	19,05	0,12	3,048	0,16	4,064	0,760	0,0706
0,75	19,05	0,16	4,064	0,08	2,032	0,774	0,0719
0,75	19,05	0,16	4,064	0,12	3,048	0,808	0,0751
0,75	19,05	0,16	4,064	0,16	4,064	0,841	0,0781

Note: The data in this table are for use with orifice equation. Flow areas are for double doors 7 ft (2,13 m) high, 6 ft (1,83 m) wide, 1,75 in. (44,5 mm) thick, and with a doorstop
protruding 0,62 in (15,7 mm) from the frame. The flow areas are evaluated by the gap method at 0,65 in, H_20 (37,3 Pa).

Table 3.2. Flow areas for the gaps around double doors.

Chapter 4: Computational assessment of pressurization or ventilation systems on loading walkways.

4.1. Basic theory and information.

4.1.1. Pool fire basics.

According to Goula and Malkotsi 2017 [9], a pool fire is characterized as a turbulent diffusion of fire that occurs above a horizontal surface where hydrocarbon fuel is vaporizing. Pool fires are controlled by buoyancy, and the fuel can be in the form of liquid, gas, or solid. The shape of the pool can vary, but usually they are circular, elliptical, and rectangular. Pool fires are characterized by parameters such as the total heat release rate, flame spread rate, and power radiated to the surroundings. The risk of a fire incident can be influenced by ambient conditions such as the presence or absence of an enclosure, wind, currents, or ventilation.

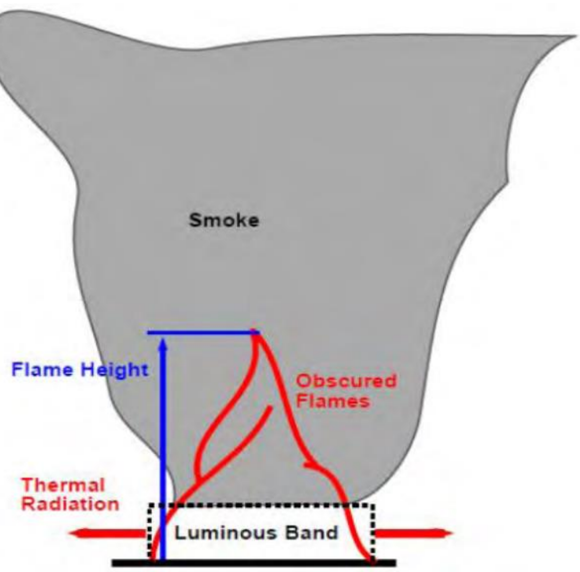


Fig 4.1. Liquid fire scheme by Christina Goula, Chrysoula Malkotsi, 2017 [9].

Pool fire behavior is importantly impacted by the fuel burning. Different fuels will have different properties such as combustion temperatures, flame characteristics, heat release or mass loss rate. As such, fuel will influence fire intensity and duration.

For the study of pool fires, computational modeling has become one of the most used and important tools in order to analyze fires and predict their behavior and impact. Through computational tools, engineers are now able to understand much more accurately pool fires and hence, develop much more optimized and effective fire safety strategies.

Overall, pool fires represent complex fire scenarios that require a deep understanding of fuel properties, fire behavior, ignition sources, fire spread potential, and appropriate suppression strategies. By acknowledging and analyzing these factors and their relation to pool fire behavior, it is possible to develop a good understanding of these types of fire hence, allowing to develop effective and efficient safety measures and plans to mitigate the risks associated with pool fires and protect both human lives and valuable assets.

4.1.2. Computational fluid and fire Dynamics basics.

Computational fluid dynamics and fire dynamic's main objective is to analyze behavior of fluid and fires focusing mainly on numerical resolution of fluid flow, heat transfer, fire behavior or flame propagation. CFD models enable the simulation of gas flow, temperature distribution, combustion processes, and the dispersion of smoke and toxic gases during fire incidents. Through these numerical solutions, it is possible to develop a detailed understanding of fire dynamics, flame characteristics, fire growth and decay, and even the relation between fire and objects of structures.

The computational methods used to be able to achieve numerical solutions employ a discretization method. The physical domain or volume is divided into discrete elements (cells) forming a mesh. By discretizing the volume, CFD and fire dynamics methods are able to solve the basics equations that define the flow, heat release and behavior in general. Differentials are now simplified in a non-continuous domain and complex governing equations such a Navier-Stokes become algebraic ones that are solved iteratively. Discretization is a key aspect of CFD and fire dynamics as it allows for the mathematical representation of complex fluid flow and fire phenomena within a computational framework.

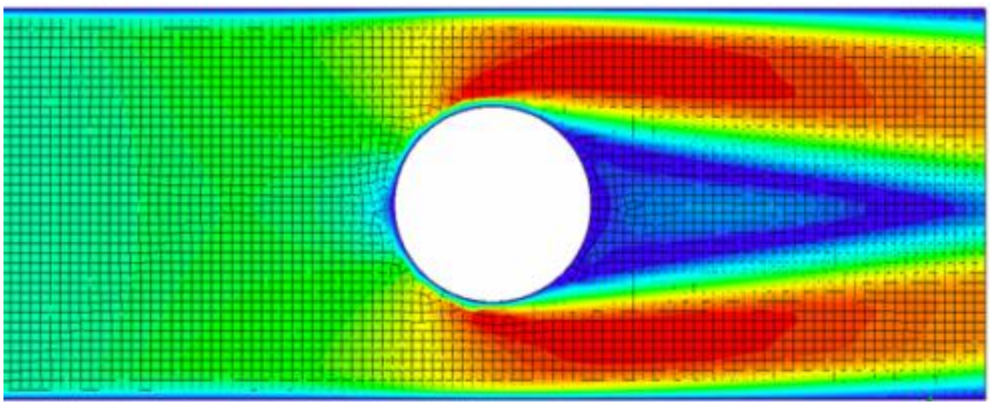


Fig.4.2. Example of a discretized domain for the study of flow around a sphere.

In summary, the utilization of computational fluid dynamics and fire dynamics allows for a deep understanding of fire and fluid behavior and the development of effective fire safety strategies.

Through sophisticated simulations, these fields enable engineers and researchers to analyze risks, optimize designs, and enhance the overall fire safety of structures and systems.

4.1.3. CFD and pool fires.

When it comes to studying the behavior of pool fires from a CFD approach, there are various important equations and factors to consider. Firstly, to be able to analyze the behavior of the various fluids concerned, it is important to consider a turbulence model, as it usually is in a CFD problem. Various of these models exists such as the Reynolds Averaged Navier-Stokes (RANS) model which is very common. This model uses the original Navier-Stokes equations regarding the conservation of momentum with a decomposition of flow velocity between an average velocity and a time-dependent component which represent the fluctuations that occur around the mean. This type of model has been widely used as it requires low computational costs due to its simplicity, especially variants such as the k- ε or k-ω variants which add two additional equations to the model. Nevertheless, the RANS models have some limitations as they only compute large scale motions and the obvious averaging of fluctuations. In the case of Fire Dynamics Simulator, the usual models are Large Eddy Simulations (LES) models. According to Rengel et al. 2019 [10], LES models can offer a more realistic looking flow, but the accuracy can be more dependent on the numerical grid as it requires for a sufficient number of grid cells.

Secondly, fuel evaporation is crucial when it comes to modeling pool fires as it is the evaporated layer of fuel that catches fire while mixed with air. As such, the model that estimates the rate of evaporation of the pool is critical when it comes to achieving an accurate simulation. In general terms, evaporation of a liquid is a function of both its temperature and pressure. As supported by Rengel et al. 2019 [10] that is also the case for evaporation of fuel pools. To be able to assess the evaporation rate, it is necessary to know the temperature of the liquid layer and the vapor pressure of the layer just above the liquid. Hence, to model the evaporation of the fuel it is necessary to solve a heat transfer problem for which various hypotheses have to be made. Firstly, the sources of heat considered are:

· Conduction from the ground.

· Radiation from the sun.

· Radiation and convection from the fire.

Secondly, as per the cited work, the liquid layer can be considered as a solid and as such, the heat transfer within itself is treated as conduction.

Thirdly, a model for combustion has to be introduced in order to quantify the products of the chemical reaction of the fuel and oxygen. As per Rengel et al. 2019 [10], an effective way to model the combustion of fuel is the Eddy Dissipation Model (EDC) which assumes an infinitely fast reaction, allowing a unique gaseous product of the reaction. Additionally, soot can be an issue when it comes to heat transfer, particularly when it comes to radiation. Hence, a model to assess the amount of soot is necessary, in the previous work a simple model is used that transforms a fraction of the carbon into soot. Other models exist as stated by I. M. Kennedy, 1997 [11], with some empirical and semi-empirical correlations. Nevertheless, these models are much more complex and represent an important computational cost.

Also, radiation is an important factor when it comes to the analysis of pool fires. The radiative transfer equations (RTEs) are the equations that describe the behavior of radiation as it interacts and propagates through the medium, in this case fuel, air and smoke. The RTEs are formulated as a set of differential equations that consider absorption, emission, scattering, and reflection, that occur as radiation interacts with the medium. Solving the RTEs can be difficult as these are complex equations with a large range of physical processes involved. Nonetheless, various numerical models exist to solve the problem such as Monte Carlo simulations, finite difference methods, and discrete ordinate methods. Additionally, various approximations and simplifications may be applied to make the RTEs to reduced computational costs depending on the situation. In the particular case of FDS, the model used is a type of finite difference method, the finite volume method (FVM).

4.2. Hypothesis.

4.2.1. Type of fuel.

Regarding the fuel that will be considered as a combustible for the pool fires, it will be the ones commercial airplanes usually use. It seems logical as the spills in the reviewed incidents are always jet fuels and are not related to the rest of the vehicles present in a runway such as cars and trucks. According to Chevron Products Company, 2007 [12], the most used fuels in commercial aviation are Jet A-1 and Jet A, which are Kerosene-type fuels. These types of fuels are used for the most common commercial airplanes in the world as the Airbus A320, the Boeing B737 or other planes from the main manufacturers such as Airbus, Boeing, Embraer or Bombardier. As per the Chevron technical review, the main difference between both fuels is their maximum freezing point which is 7ºC lower for Jet A-1. Nevertheless, apart from the difference in additives that allow different maximum freezing points, both fuels are almost identical in behavior.

Nonetheless, these types of fuels are composed by tenths if not hundreds of different carbon chains and other components. Many of these complex fuels have additives and other products in order to improve their behavior, efficiency and response to different conditions and situations. Nevertheless, in this study, for simplification, not all components will be taken into a account and a simplified fuel will be used. According to S. C. Moldoveanu, 2019 [13], n-dodecane is one of the main components in kerosene and jet fuels. The pyrolysis of dodecane has been commonly used to understand the behavior of jet fuels. As such, for the simulated model that will be employed, the fuel used will consist of n-dodecane per its similar behavior as it altogether simplifies the model.

4.2.2. Distance to the walkway and flame

To be able to assess the performance of the pressurization system and its ability to not let any smoke inside the walkway, the distance to the pool fire has to be determined, as the amount of smoke arriving to the jet bridge could greatly change. Nevertheless, in the reviewed cases, it appears there is not additional information that could indicate the distance between either the gate or the walkway, to the fuel fire. As such, it seems appropriate to use the worst case scenario to assess the performance of the pressurization system for the loading walkway. The parameter for determining the worst case scenario is the one that would make fail the pressurization system at its main task: avoid smoke to enter the jet bridge. For that, the worst location for the pool fire to be located is directly under the loading walkway, as it is where the biggest amount of fumes and smoke can enter the walkway. Additionally, as the walkway is elongated, the fire could be located at various points under the bridge between the terminal and the aircraft. Nevertheless, the lowest point of the walkway is the point where the flames can be closer, and it is located at the nexus with the aircraft. Coincidently, it is also the point where the most leak areas as located hence, making it the most sensitive location for smoke infiltration from an underneath fire. As such, to be able to assess confidently the system's performance, the fire will have to be located underneath the walkway, where it couples with the aircraft, that is the worst case scenario location.

When validating the good functioning of the pressurization system through CFD simulations, a variety of diameters for the pool fire will be assessed. Nevertheless, it is necessary to evaluate which will be the bracket of this value as there will be a maximum diameter for which it will not be necessary to evaluate the performance of the system. The maximum pool fire diameter will be estimated as the one that could lead to a flame impingement on the loading walkway and thus, the total loss of the loading walkway. According to ASTM E119 [14], structural steel is assumed to fail at 537,8 ºC (1000 ºF) and considering that the pool fire flames could be at a temperature 800-900ºC, the steel structure could be rapidly lost in the event of flame impingement.

In the case that will be examined, the maximum height for the flames is 3.5 m as it will lead to flame impingement for the selected jet bridge. To be able to estimate the maximum diameter that could lead to that flame height, the study by M. Muñoz et al. 2004 [15], will be used as it states direct formulation of the relation between flame height and pool diameter for the case involved in this study. This will serve as a first approximation for the flame height and pool diameter as the hydrocarbon used in the mentioned work is gasoline. The simulation that will be perform will give a more accurate value regarding the pool diameter for which flame impingement can happen. As such, the first simulations will be performed with the approximation here presented.

The assumptions for this approximation are the hydrocarbon is gasoline, the ambient air temperature is 20ºC, there is no wind and the flame length selected for no impingement to happen is the maximum flame height and not the medium height. According to M. Muñoz et al. 2004 [15] the following equations give a relation between flame height and pool diameter:

$$\frac{L}{D} = a'(m^*)^{b'}(u^*)^{c'}$$

$$m^* = \frac{m''}{\rho_a\sqrt{gD}}$$

$$m'' = \dot{m}''_\infty(1 - e^{-k'D})$$

D *Diameter of the pool m*

L *Maximum flame height m*

a' *Constant parameter with a value of* 8.44 *for maximum flame height*

b' *Constant parameter with a value of* 0.298 *for maximum flame height*

c' *Constant parameter with a value of* − 0.126 *for maximum flame height*

m^* *Dimensionless burning rate*

ρ_a *Air density at ambient conditions*, 1,204 $kg\ m^{-2}$

g *Gravity acceleration* 9,81$m\ s^{-2}$

u^* *Dimensionless wind rate equal to* 1 *in windless conditions*

m'' $\quad$ $Mass\ burning\ rate\ kg\ s^{-1}m^{-2}$

m''_{∞} $\quad$ $Maximum\ mass\ burning\ rate\ kg\ s^{-1}m^{-2}$

k' $\quad$ $Constant\ with\ value\ of\ 1.173\ m^{-1}\ for\ gasoline$

As such, we obtain a preliminary value of 1,45 for the pool diameter which we will round up to 1,5 m.

4.3. Scenarios and model.

4.3.1. Scenarios.

As previously explained, the air velocity inside the jet bridge will vary between 0,15 and 0,5 m/s to be able to ensure the comfort of people inside it, the optimum value being comprised between 0,15 and 0,25 m/s. With this air velocity bracket in mind, various scenarios will be assessed, to, not only evaluate the pressurization system at full capacity (air velocity of 0,5 m/s), but also at its optimum operating conditions. This optimum equals to an air velocity of 0,15m/s as it is comprised in the optimum comfort bracket (0,15-0,25 m/s) for humans as well as being the most economical one, reducing the power needed.

Moreover, it is interesting to evaluate the possibility of natural ventilation as it would be the most economical option if found valid. Natural ventilation relies on passive airflow to evacuate air, taking advantage of processes such as pressure differentials that result in the circulation of air or the buoyancy effect. This pressure differentials may be caused by a difference in temperature, wind or other natural airflows, and needs to be studied for the ventilation system to be effective. Hence, natural ventilation systems do not require high infrastructure or equipment, nor they need mechanical moving parts such as fans in case of HVAC's. As such, these types of systems represent a saving in operating costs, not needing a power input, such as HVACs need, and less maintenance. Furthermore, the use of natural ventilation instead of a pressurization system will also imply a reduction in investment.

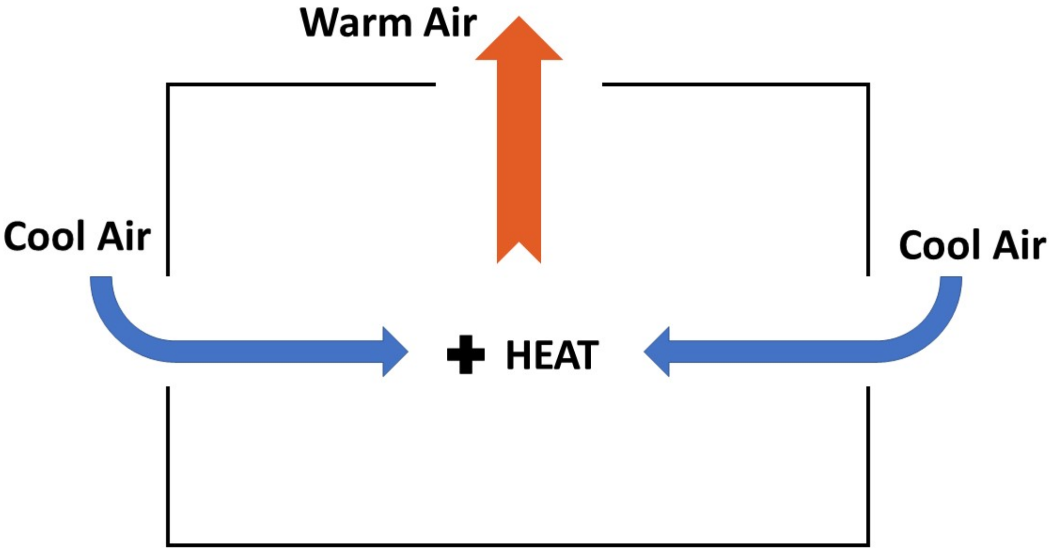


Fig 4.2. Schematic of Thermal buoyancy induced natural ventilation.

Additionally, we have obtained a maximum value for the pool diameter of 1,5 m for the loading walkway not to be engulfed in the flames, a case for which the pressurization system is not expected to maintain a valid environment and for which it is not designed. Accordingly, the systems will be able to maintain a sufficient environment for any pool diameter under 1,5 m and as such, these will be tested for various diameters, in particular pool fires of 0,5 m, 1m and 1,5 m in diameter.

With the previous information, 9 simulations will be set to assess all the situations described and are summarized in the following table:

Scenario	Smoke Control System	Pool Diameter
1	Pressurization (3000 m^3/h for 0,15 m/s)	0,5 m
2	Pressurization (9800 m^3/h for 0,5 m/s)	0,5 m
3	Natural ventilation	0,5 m
4	Pressurization (3000 m^3/h for 0,15 m/s)	1 m
5	Pressurization (9800 m^3/h for 0,5 m/s)	1 m
6	Natural ventilation	1 m
7	Pressurization (3000 m^3/h for 0,15 m/s)	1,5 m
8	Pressurization (9800 m^3/h for 0,5 m/s)	1,5 m
9	Natural ventilation	1,5 m

Table 4.1. Summary of the 9 scenarios evaluated.

4.3.2. Fire Dynamics Simulator (FDS).

The assessment of the scenarios previously described will be performed through simulations using Fire Dynamics Simulator (FDS). FDS is a computational fluid dynamics software (CFD) that specializes in fire dynamics in different conditions and environments. Apart from using fluid dynamics equations or heat transfer ones like other CFD software, FDS additionally employs other models that allow users to predict complex fire dynamics such a smoke movement or flame spread. By allowing to simulate complex fire scenarios and allowing to model the behavior between fire, airflow, and structures, FDS has become a widely used software to analyze fire protection designs and developing effective safety strategies.

To be able to use FDS more effectively, PyroSim has been used in this study. PyroSim is a user interface for FDS that allows users to create, run and analyze simulations more easily and intuitively. More particularly, it simplifies the creation of 3D environments and adds a variety of tools and features to simplify our work.

4.3.3. FDS model.

In order to create a valid FDS Model to assess adequately the different scenarios previously described, various factors needed to be considered and modeled. Hence, the model can be divided into:

· Geometry and leak areas.

· Devices.

· Boundary conditions.

· Mesh.

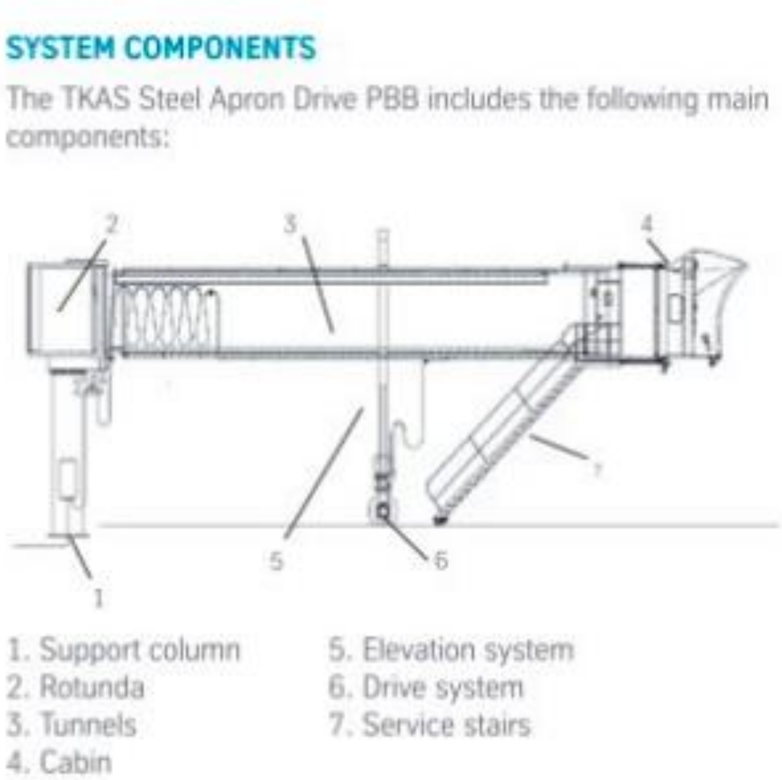


Fig 4.3. Schematic and parts of ThyssenKrupp's walkways.

Following the plans and measurements of the technical documentation from the ThyssenKrupp's TB 45/26.5-2 walkway model, a 3D model has been made. As such, the tunnel has been modelled with an interior width and height of 2 m and 2,5 respectively. For the exterior, the width and height of the tunnel are 2,5 m and 3 m respectively and a total length of 45 m. The tunnel has been divided into 9 sections of 5 m each, making up for the total 45 m. As previously explained, the maximum vertical distance between the walkway and the pool is 3,5 m. As a result, the distance between the floor and floor of the last section of the tunnel is exactly 3,5 m.

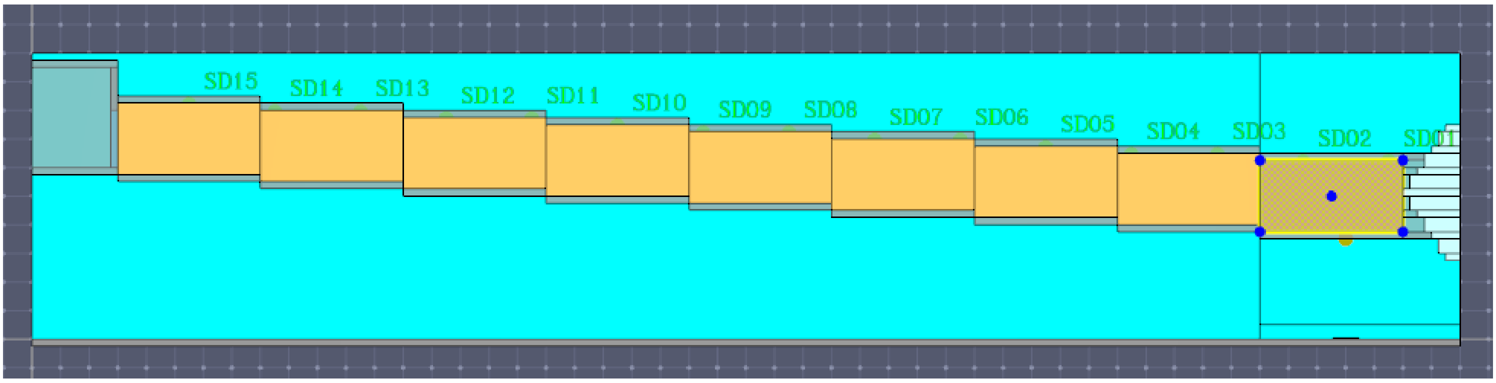


Fig 4.4. Side view of TB 45/26.5-2 PyroSim model.

Usually, jet bridges present a downwards tilt as the cabin height to the tarmac is lower than the height from the terminal. As a simplification of this tilt, it has been decided to place all the tunnel's sections in a step disposition with a heigh difference of 0,25 m between every adjacent section. This number has been selected as it represents the thickness of the walls, if the step had been greater, the interior of the tunnel would have been open to the exterior.

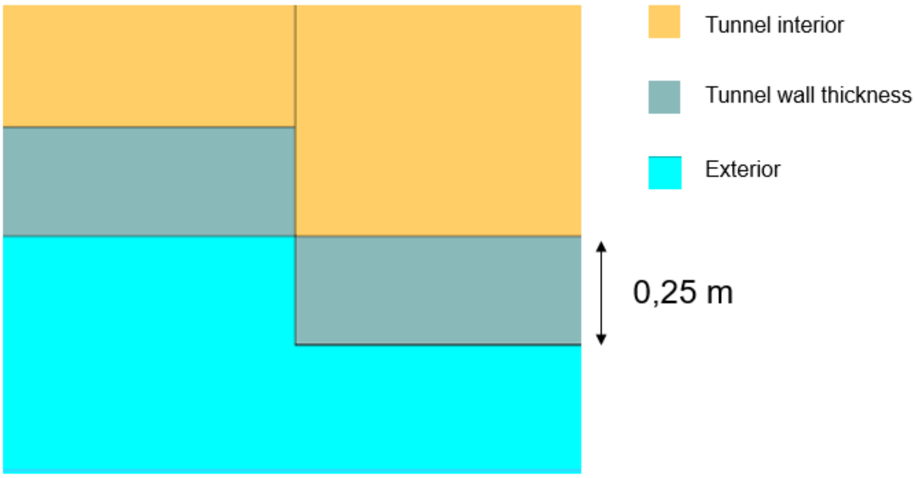


Fig 4.5. Schematic exemplification for the chosen step height.

Additionally, the rotunda and its door have also been modeled according to the specified dimensions, together with the cabin door. Nevertheless, for simplification purposes the rest of the cabin, the elevation and drive systems, the support column and the system stairs have not been modeled as it has been estimated their influence regarding smoke and ventilation behavior should be minimal. The materials assigned in the model for the jet bridge are mainly steel, except the doors which were assigned glass.

Once the geometry has been modeled, the leak areas also have to be accounted for, in relation to the following values obtained in Chapter 3:

· Loading walkway external walls (Tunnel): 1,7·10-4 m^2/m^2 .

· Double door between the terminal and the walkway (Rotunda): 0,0781 m^2.

· Loading walkway boarding gate (Cabin): 1,2·10-3 m^2/m^2.

To introduce the leak area to the model, it is necessary to multiply this value by the area to which it applies. The tunnel has been divided, as discussed in 9 section and each of these sections has 4 walls noted Bx for the floor, Tx for the roof, Lx for the left wall and Rx for the right floor. The letter x represents the number of the section, starting from the closest section to the airplane. The four walls nearest to the airplane have been accounted with the relative leak area related to the boarding gate of 1,2·10-3 m^2/m^2, as it is its location. The rest of the walls have been accounted to the normal leak area value for walls of 1,7·10-4 m^2/m^2. The final values introduced are summarized in the following table.

Name	Relative leak area m^2/m^2	Total area m^2	Leak area m^2
B1 and T1	$1,2\cdot10^{-3}$	10	$1,2\cdot10^{-2}$
B2 and T2	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
B3 and T3	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
B4 and T4	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
B5 and T5	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
B6 and T6	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
B7 and T7	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
B8 and T8	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
B9 and T9	$1,7\cdot10^{-4}$	10	$1,7\cdot10^{-3}$
L1 and R1	$1,2\cdot10^{-3}$	12,5	$1,5\cdot10^{-2}$
L2 and R2	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$
L3 and R3	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$
L4 and R4	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$
L5 and R5	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$
L6 and R6	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$
L7 and R7	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$
L8 and R8	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$
L9 and R9	$1,7\cdot10^{-4}$	12,5	$2,125\cdot10^{-3}$

Table 4.3. Summary table of model's surfaces, total and leak areas.

Additionally, the leakage through the double door between the rotunda and the terminal door has also been taken into consideration with the value previously stated.

Also, some devices have been added to the model such as an HVAC and smoke detectors. Per the smoke detectors, PyroSim includes them in their library, in this case 15 clearly photoelectric detectors, with an obscuration threshold of 3,24 %/m, have been introduced along the tunnel. According to NFPA standards set in NFPA 72 [16] section 17.7.4.2.3.1.(2): "*All points on the ceiling shall have a detector within a distance equal to or less than 0.7 times the nominal 30 ft (9.1 m) spacing (0.7S).*". Hence, the maximum spacing between the smoke detectors is 6,37 m. By placing 15 detectors, a 3 m spacing is achieved hence, complying with NFPA standards. This number has been chosen to cover the walkway's tunnel in the most accurate way possible, while complying with American standards.

Regarding the HVAC, a box shaped geometry has been modeled with 0,25x0,5x1 m dimensions and placed at the entry of the tunnel, right next to the rotunda. These dimensions have been chosen from a variety of commercial size grids available, upon the available one, the larger ones have been selected to reduce air velocity in order to maintain a comfortable environment. The location is logical as the HVAC must introduce clean air to the jet bridge. The best air available is the one at the Terminal, as the exterior could be filled with smoke. Depending on the scenario simulated, a different airflow has been assigned. This airflow will cross the HVAC's plane that is orthogonal to the tunnel's direction. The HVAC has been programmed to be activated when two or more of the smoke detectors reach their obscuration threshold.

Additionally, there are 3 scenarios (3,6 and 9) in which the system employed is a natural ventilation one. For these three cases, no HVAC is being employed but two vents have been added. These two vents are placed on the ceiling of the tunnel in such way the tunnel is divided into 3 equally long parts between vents. The dimensions are 1x1 m for both of them. For these natural ventilation scenarios, the same triggering system has been used, that is at least two activated smoke detectors. In the FDS model, when the system is triggered the ceiling vents change and are no longer considered walls as such, allowing air flow and ventilation.

A crucial element in this model are the boundary conditions. Boundary conditions are of the upmost importance in CFD simulation as they set the limitations with the domain, and they control flow behavior. Boundary conditions add equations and information to the system of equations FDS has to solve in order define the flow, the heat transfer and more, and as such, solve the problem. The boundary conditions selected for this model are the following:

· Specified air flow at the HVAC. As previously explained, it varies depending on the scenario selected.

· No slip or wall boundary conditions at every solid surface in the model (ground floor, jet bridge, airplane, etc).

· Open vent: this boundary condition applies at the limit of the control volume in order to allow air flow from entering or exiting the volume.

· Mass loss rate of the pool fire.

Evaluating the mass loss rate of a fire is critical when evaluating a fire and furthermore, when creating a model to simulate fire scenarios such as in this study. This rate is pivotal as it directly influences fire growth, heat release, combustion products or smoke production. In order to have reliable results and safety assessments, as the evaluated jet bridge case, accurate estimation of this variable is a key requirement. Mass loss rate can be a function of time and it usually is. Various models exist to model the rate at which fuel is consumed, usually employing empirical correlations depending on the precise context and type of fire. In this case, the constant mass loss rate model will be employed as it significantly simplifies the simulation. Additionally, this model does work well when evaluating the steady state of the fire. Regarding the scope of this project, the evaluation of performance of the pressurization system at a steady state is the of main interest hence, the use of this particular model. To estimate the exact value of the constant loss rate, the equations described in by M. Muñoz et al. 2004 [15], will be employed:

$$\dot{m}'' = \dot{m}''_{\infty}(1 - e^{-k'D})$$

$\dot{m}''$ *being the constant mass loss rate* $(kg\ s^{-1}\ m^{-2})$.

$\dot{m}''_{\infty}$ *being the maximum mass loss rate* $(kg\ s^{-1}\ m^{-2})$, *which is estimated to be* 0,083 *for gasoline*.

k' *being the constant parameter* $(\ m^{-1})$, with a value of 1,173 for gasoline.

D *being the pool diameter* $(\ m)$.

For this estimation, dodecane is considered to behave similarly to gasoline and gasoline values can be valid for the study. As such, mass loss rates will be:

· 0,03683 kg/(m²·s) for a pool diameter of 0,5 m.

· 0,05732 kg/(m²·s) for a pool diameter of 1 m.

· 0,06871 kg/(m²·s) for a pool diameter of 1,5 m.

Correlation parameters for mass burning rate

	$\dot{m}''_\infty$ ($kg\,m^{-2}\,s^{-1}$)	k' (m^{-1})
Gasoline	0.083	1.173
Diesel	0.062	0.63

Table 4.4. Values estimated for gasoline and diesel for maximum mass loss rate and k'.

Finally, for CFD simulations, a good mesh is indispensable for accurate results and validation. For this model, a mesh employing 597.760 rectangular cells has been created. Three distinct mesh zones have been defined. First, a specific mesh for the pool and its zone has been created in order to have a finer mesh in the neighboring zone, as it is a crucial zone, and its behavior needs smaller cells to have accurate results. Of the total 595.760 cells, 280.000 0,05x0,05x0,05 m cells belong to this zone. This first mesh englobes a 0,5 m layer over the ground floor in 7x10 m rectangle around the fire. A second mesh has been created for the same rectangle but with heights between 0,5 and 10 m, with 42.560 cells and with 0,25x0,25x0,25 m dimensions. Finally, the rest of the volume has also been meshed, with 0,25x0,25x0,25 m cells and a total number of 275.200 of them.

All three of the meshes have passed the mesh alignment test, which is a test to evaluate the quality of the mesh that considers various important factors to evaluate the validity of it such as displacements, deformation or skewness.

Mesh	Nº of cells	Cell dimensions	Location
1	280.000	0,05x0,05x0,05 m	0,5 m layer above ground and around pool fire.
2	42.560	0,25x0,25x0,25 m	Above mesh 1, heights between 0,5 and 10 n
3	275.200	0,25x0,25x0,25 m	Rest of domain
TOTAL	597.760		

Table 4.5. Table summary of the created mesh.

4.4. Validation criteria.

The main objective of both the pressurization system and the natural ventilation one is to protect passengers from an outside fire, more particularly from the entry of smoke. Loading walkways are a crucial mean of egress that must have a good environment to ensure a safe evacuation from the aircraft in the case of a fire.

The simulations modeled for the described scenarios are meant to validate these systems in these situations but for that, some specific criteria must be set in order to state with confidence that these systems ensure a safe environment for an evacuation.

In order to set specific criteria to validate the performance of these systems, we will refer to the same standards that made mandatory pressurization systems in loading walkways, that is NFPA standards. As set in NFPA 92 [5] section 4.1.2 (3), the design objective in this case is "*Maintaining a tenable environment within all exit access and smoke refuge areas access paths for the time necessary to allow occupants to reach an exit or smoke refuge area."* In annex M of NFPA 92, there are specific criteria on what a "tenable environment" is according to American standards that rely on 4 different analyses: heat, toxic gasses and thermal radiation. Nonetheless, the scope of this study is to provide an analysis in response to NFPA 415 [1] that requires systems to protect jet bridges against smoke from outside fire. In consequence, the criteria that will be used to validate the system will be regarding both toxic gasses and visibility, neither heat nor thermal radiation.

4.4.1. Validation criteria for toxic gases.

According to section M.3.7.1 of NFPA 92 [5], air carbon monoxide (CO) content must be controlled. The limits for CO content are defined through the following equation:

$$FED_{CO} = \sum_{t_1}^{t_2} \frac{[CO]}{35000} \Delta t$$

FED_{CO} *being the fractional effective dose.*

Δt *is the time increment in minutes.*

$[CO]$ *is the average concentration of CO in ppm over the period.*

The resulting fractional effective dose from this equation has an uncertainty associated of 35 % which has to be considered.

To assess if the carbon monoxide content is within the tenability standards, it has to be lower than the limit values indicated on the following table provided in NFPA 92 [5].

Time (min)	Tenability Limit		
	AEGL2	0.3	0.5
4	—	1706	2844
6	—	1138	1896
10	420	683	1138
15	—	455	758
30	150	228	379
60	83	114	190
240	33	28	47

Table 4.6. Maximum carbon monoxide exposure according to section M3.7.1 of NFPA 92.

There are various thresholds available:

· 0,5 is typical for adult and healthy population.

· 0,3 is the most used value and englobes more sensitive population.

· AEGL2 is usually used for general population, including the most susceptible individuals.

For the purpose of this study, the most common value of 0,3 will be employed. Additionally, the time spent in these conditions must be estimated in order to identify the effects of CO in individuals and thus, the tenability limit. Hence, to acknowledge the time spent in the jet bridge it is necessary to have an approximation of the walking speed of passengers in an evacuation situation. According to Karl Fridolf et al. [17] there are various methods to estimate walking speed when visibility is reduced. The first method does not cluster people and treats the group homogeneously, assigning a speed of 1 m/s when visibility is higher than 3 m and 0,3 m/s in the rest of cases. On the contrary, the second method clusters people in 3 groups which will be assigned different speeds in both scenarios (visibility higher than 3 and visibility lower or equal to 3). The last method assigns a random value from a normal distribution to estimate speed. In the case of this particular study, for the sake of simplicity, the first method will be used. As such, the times spent inside the loading walkway will be:

$$\text{If visibility} > 3 \qquad \mathrm{t} = \frac{\mathrm{d}}{\mathrm{v}} = \frac{45}{1} = 45\ \mathrm{s}$$

$$If\ visibility \leq 3 \qquad \mathrm{t} = \frac{d}{v} = \frac{45}{0{,}3} = 150\ s$$

$\text{d is the walkay's lenght, 45 m in this case.}$

The presence of CO_2 and its level is also a key variable to control in order to safely assess whether an environment is safe and tenable. According to the Occupancy Safety and Health Administration [18] the limit to not be exceeded for a 10 min period is 30.000 ppm of CO_2. This will be the criteria used in this study as the NFPA does not present specific criteria for CO_2 levels. Additionally, the 10 min period has been selected as it is the smallest period for which a threshold as been specified. As previously stated, passengers will be exposed 45 s to the gases in case of visibility higher than 3 m and 150 s for poor visibility. Hence, a criteria involving a 10 min period will be more restrictive and will maintain a high security ratio.

4.4.2. Validation criteria for visibility.

As stated by section M3.8 of NFPA 92 [5], *" Visibility through smoke should be maintained above the point to which a sign internally illuminated at 80 lux (7.5 ft candles) is discernible at 30 m (100 ft) and doors and walls are discernible at 10 m (33 ft). These distances can be reduced if demonstrated by an engineering analysis".* Nevertheless, in section M3.8.2 the previous statement is amended for spaces like a loading walkway, in this case confined egress routes: "*For confined egress routes containing little to no obstructions and where the exits are readily located in any direction of travel (e.g., small rooms/balconies or hotel corridors with exit stairs at remote ends), the visibility threshold can be reduced to the point at which an exit sign is discernible at no less than 10 m (33 ft) and doors and walls are discernible at no less than 3,75 m (12 ft)."* As such, the visibility criterion is that in no case the mean visibility of the simulation will be under 10 m, as it is more restrictive than 3,75 m.

4.3. Results assessment.

For the review of the results found, various variables will be considered. First, the temperature of the closest point of the jet bridge to the pool fire has been monitored and has been evaluated. The walkway's steel structure has a limited working temperature of around 537,8ºC, if this limit is surpassed the walkway may collapse. If this is the case, smoke will not be the focal point of the security strategy but rather fire prevention through systematic cleaning of the area to avoid fuel spills.

Secondly, temperature, air speed and visibility contours and distribution have been reviewed. Both temperature and air speed are important factors in order to evaluate if a comfortable environment is being maintained. As previously stated, the comfort objective is to keep air speeds under 0,5 m/s. Additionally, according to ASHRAE Standard 55 [6], if air velocities are being maintained within acceptable values, temperature should not exceed 26ºC to keep a comfortable environment for human presence.

Another key aspect in order to analyze both the pressurization system and the natural ventilation one, is their behavior and performance during the scenarios. As such, the times at which they were activated will be studied and subsequently, the impact of the activation upon smoke presence, temperature, and the rest of the relevant factors.

Finally, another important source of information and results are the data provided by FDS regarding CO and CO_2 presence and smoke detector's visibility. The results assessment has been fulfilled with all the key information just described.

4.3.1. Structure temperature.

The results obtained regarding temperature at the hottest point of the structure (closest to the fire) are summarized in the following table, both the maximum and average temperatures are included:

Scenario	1	2	3	4	5	6	7	8	9
Max Temperature (ºC)	151,4	151,4	155,3	407,5	407,5	423,0	746,0	746,0	859,52

Table 4.7. Maximum structural temperature for each scenario.

As explained, the main objective of measuring the temperature at the closes point of the structure is to be able to ensure there will not be any collapse. The intent of the study is to guarantee a ventilation or pressurization system is reliable enough to protect passenger's egress from smoke in the most efficient way, if possible. As such, evaluating the system for a situation in which there is a high risk of structural failure would cause to develop over performing systems.

In this regard, scenarios 1 to 6 are excluded from this problem as in all of them, the maximum structural temperature would be lower than ASTM E119 [14] maximum temperature of 537,8 ºC. Nevertheless, that is not the case for scenarios 7, 8 and 9, those with a pool diameter of 1,5 m, would be at a high risk of a structural failure as their maximum temperature is far higher than the limit. For scenarios 7 and 8 the maximum temperature would exceed by more than 200ºC the limit, 300ºC for scenario 9. As such, the rest of results for these three scenarios will not be relevant even if they will still be reviewed to assess how valid are the system even in more pessimistic scenarios.

4.3.2. System activation.

In order to evaluate the results and correctly assess that the protection systems have efficiently maintained a tenable and comfortable environment, it is necessary to evaluate how and when they have impacted the situation. Hence, before assessing the results, the activation of the protection will be reviewed.

On the one hand, this analysis will help to understand how the systems have improved the inside environment and how well they have impacted the situation, allowing us to separate the data influenced by the protection systems and the data that is independent of either the ventilation system or the pressurization one. On the other hand, reviewing the activation system, will allow to better understand when the protection system should be activated in order to ensure more efficiently the safety of the passengers and the tenability of the environment.

As such, here are summarized the activation times of each scenario, knowing the moment at which they have been activated will be crucial to analyze the rest of the results.

Scenario	1	2	3	4	5	6	7	8	9
Activation time (s)	330,0	330,0	334,0	168,0	168,0	166,0	74,0	74,0	70,0

Table 4.8. Protection system activation time for each scenario.

4.3.3. Contours.

Through PyroSim, the contours of mean visibility, temperature and velocity have been obtained for the 900 seconds of simulation. These contours have been calculated at the side slice of the model that separates it in two symmetrical parts. Before the activation of the systems, these three variables only depend on the pool diameter as the protection system have not yet acted on the inside environment. As such, before the activation, the results will be assessed by grouping the simulation in groups of three having the same diameter, hence disposing scenarios 1,2 and 3 together, 4,5 and 6 and 7,8 and 9 together. Nevertheless, after the activation every scenario has been treated differently regarding contour analysis.

4.3.3.1. Visibility contours before activation.

The first contours analyzed are the visibility one. As we can see in the contour below, just after the beginning of the simulation, there is a decrease in visibility just under the jet bridge.

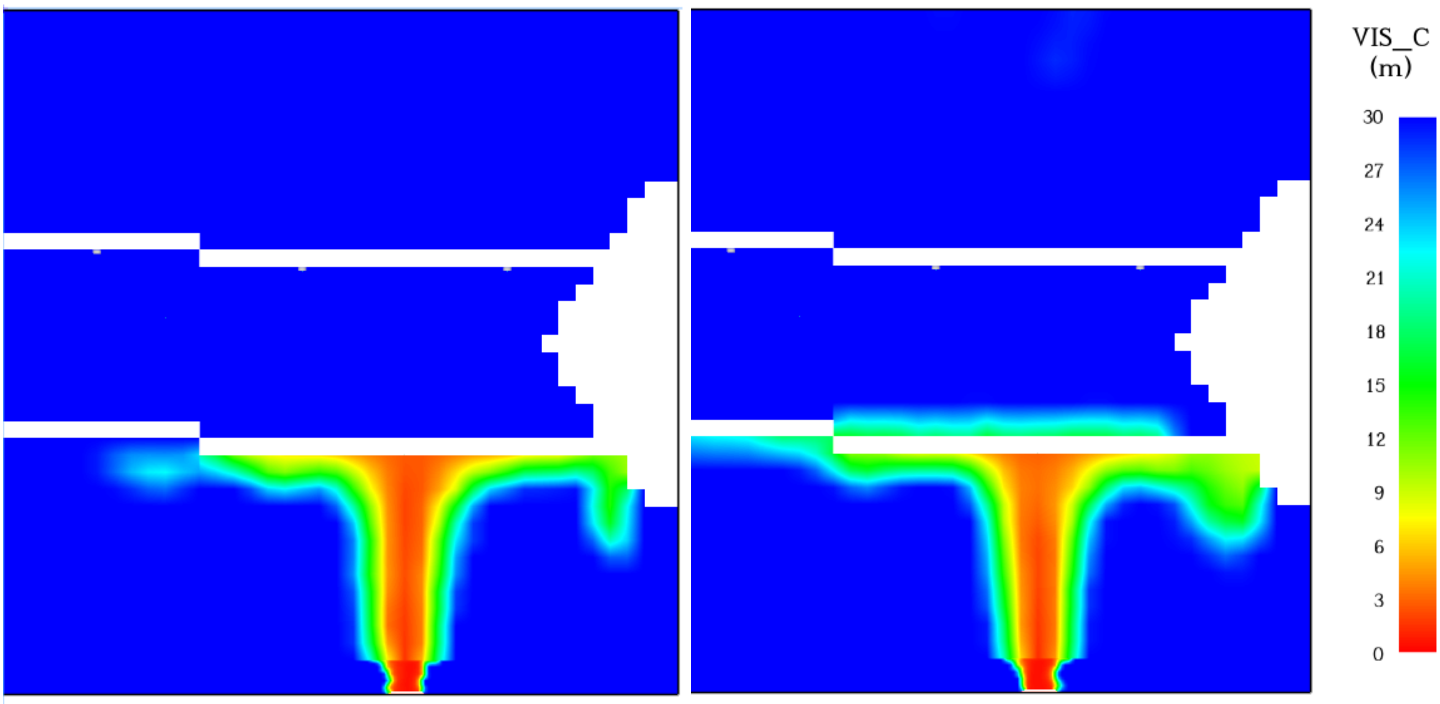


Fig.4.6. Visibility contour for scenario 1, t=6 s and t = 55 s.

Nevertheless, for scenarios 1,2 and 3 visibility begins to drop slightly inside the jet bridge around t=55 s. Near the walkway's floor, just at the level of the fire, a slight drop in visibility begins to appear, dropping from the standard 30 m to around 18 m. Nonetheless, the reduction in visibility is still slight and confined to a small area.

From that point on, visibility starts to be progressively reduced. More specifically, smoke starts to go up, not only staying a ground level like at t = 55 s. At t = 325 s, 5 s before the activation in scenarios 1 and 2, and 9 s before activation for scenario 3, the reduction in visibility has spread across the entire height of the interior of the walkway. Hence, a reduction in visibility of around 15 m appears now at eye level. Luckily, this 15 m visibility at eye level is still over the validation criteria for visibility of 10 m.

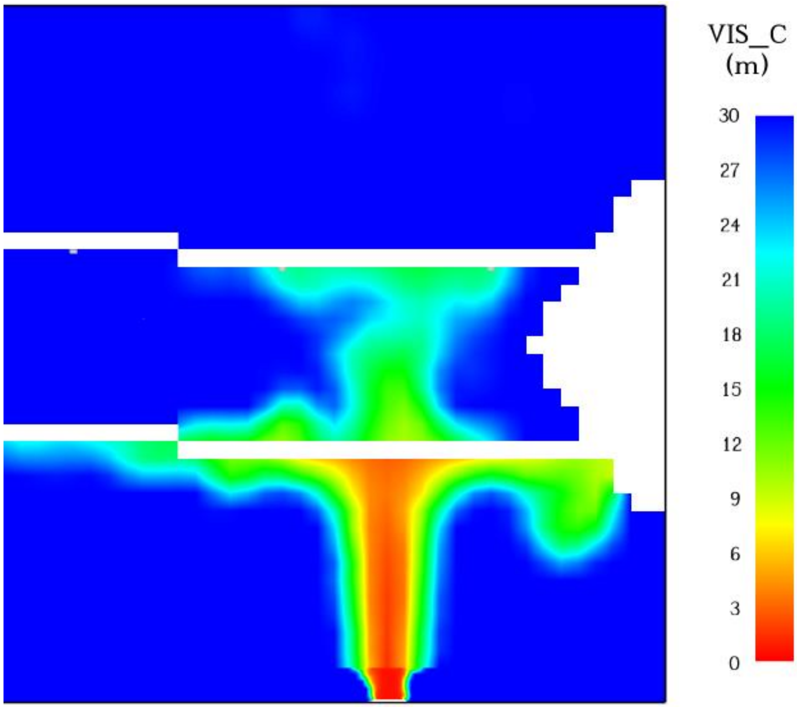


Fig.4.7. Visibility contour for scenario 1, t=325 s.

As in the first three scenarios, some time is needed for visibility to start decreasing on the inside of the walkway. Nevertheless, for scenarios 4,5 and 6 it has taken much less time for visibility to start to drop, and around 12 s after the start it starts to be noticeable. As a comparison, it took around 55 s in the three first scenarios. As in the previous cases, this drop in visibility appears at floor level with visibility levels around 18-21 m.

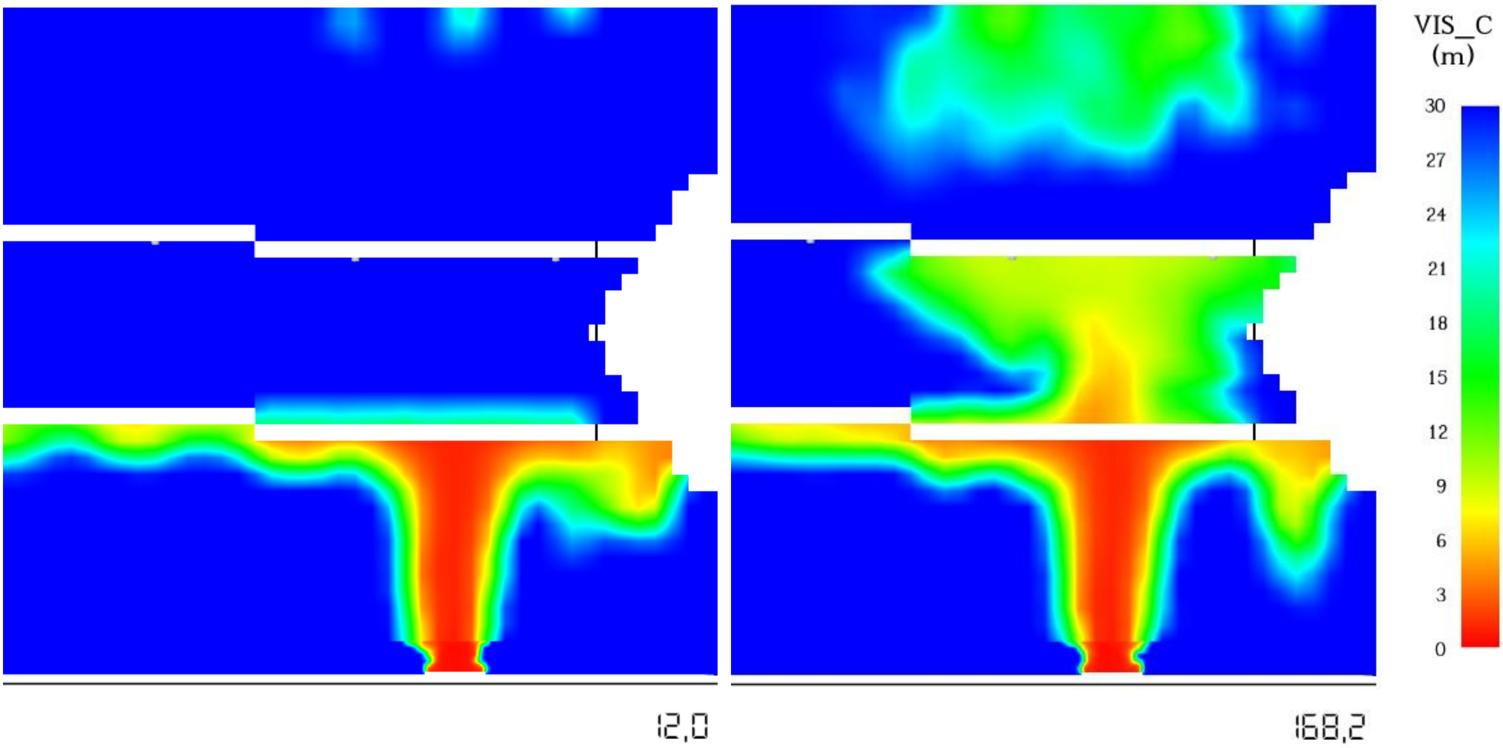


Fig.4.8. Visibility contour for scenario 4, t=12 s and 5 =168,2 s.

From that point on, visibility continues to drop slightly. Not only the drop becomes more acute, but it also spreads to the whole section of the loading walkway. The process continues until the activation at t = 168 s. At this moment, visibility has dropped across the whole first 3 m long section and across the entire heights of the tunnel. In this particular moment, visibility has dropped to around 9-12 m in the first section, with important areas with very reduced visibility of around 3 m. As such, it can be confidently stated that, in spite of further data regarding visibility, visibility has dropped under the tenability threshold of 10 m, awaiting system activation.

As expected, for scenarios 7,8 and 9, behavior is very similar but more accelerated as the pool diameter is bigger. Hence, visibility decrease starts to be noticeable around t = 8 s. Just before activation, visibility distribution is very similar to scenarios 4,5 and 6 with average visibility around 9 m, and even dropping to 3 m in some areas. Nevertheless, it seems the reduced visibility areas are bigger a more spread out. As in previous scenarios, it seems that a tenable environment is not maintained as visibility drops to low in some zones.

4.3.3.2. Visibility contours after activation.

For the first scenario, visibility results seem to indicate that the pressurization system worked effectively at managing a good visibility. After one minute of activation (t = 390 s), visibility was recovered almost everywhere inside the loading walkway. Some areas still had a reduced visibility but the visibility levels in this area was still above the 10 m threshold, with values around 15 m. Additionally, around three minutes after activation (t = 510 s), visibility was completely recovered and no area inside the loading walkway had values under the initial 30 m visibility.

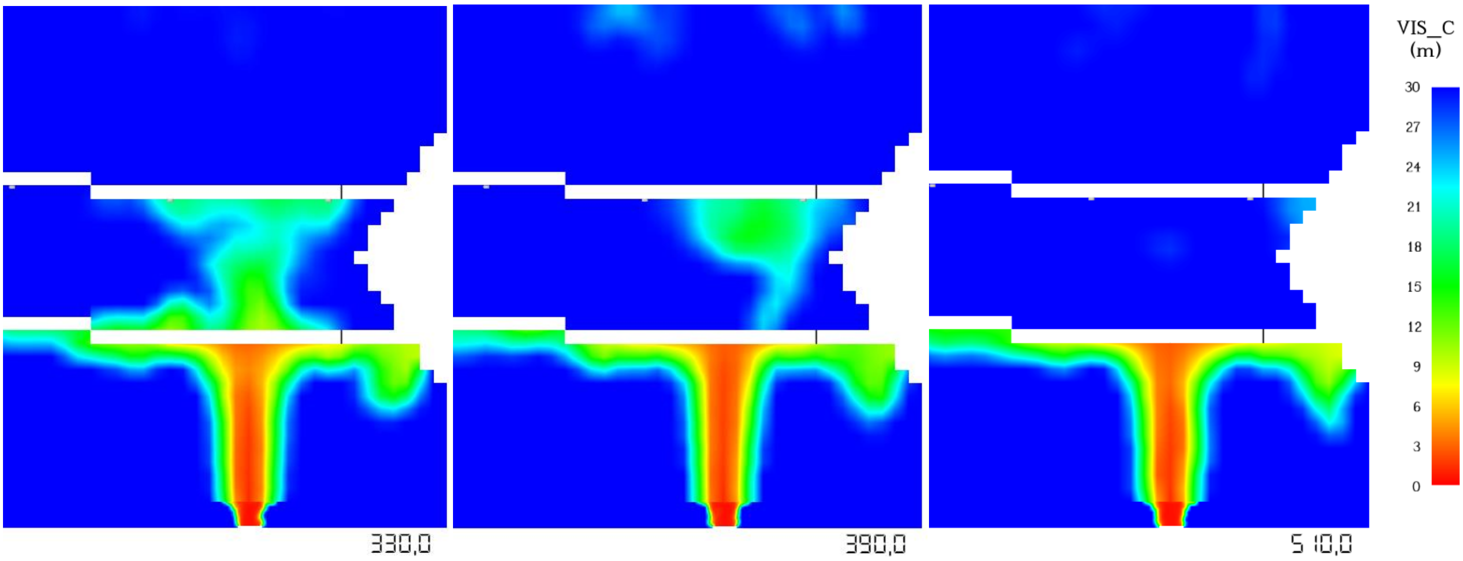


Fig.4.9. Visibility contour for scenario 1, at t=330, 390 and 510 s.

In the case of scenario 2, visibility contour results are very similar to scenario 1. From activation on, the pressurization system starts to quickly recover visibility levels and as in scenario 1, after one minute of activation, most areas have a normal 30 m visibility. Only some small areas still have lower visibility levels around 15-18 m but still above the 10 m limit. Nonetheless, it is noticeable that due to an increased air flow, visibility is recovered much quicker as after only one minute and a half (t = 420 s), visibility is completely recovered in all areas, that is approximately one minute and a half sooner than in scenario 1.

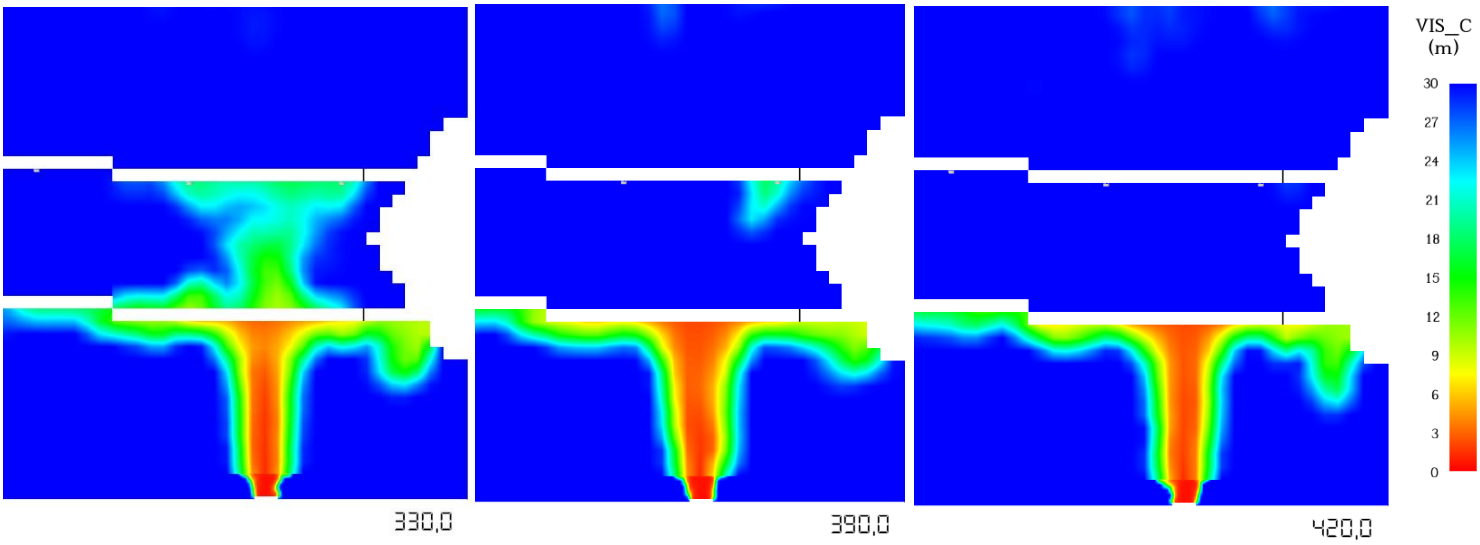


Fig.4.10. Visibility contour for scenario 2, at t=330, 390 and 420 s.

Visibility behavior in case 3 is quite different from the two previous one. This is normal as this scenario uses natural ventilation instead of a pressurization system. Nonetheless, it seems the natural ventilation approach ensues poorer results regarding visibility. Actually, by the visibility contours, it seems that instead of recovering visibility levels, it spreads the smoke in a larger area. After four minutes from activation, visibility levels have not improved. Actually, they are even worse as the reduction in visibility has spread to a larger area. It is true that visibility levels are manageable as they are around 12-15 m in most areas hence, above the 10 m threshold. At the end of the simulation, more than 9 minutes after activation, visibility was still not recovered. As it happens, the direction of flow is quite visible through the contours, has visibility levels are down following the path from the original compartments to the ceiling vents to the left of the loading walkway.

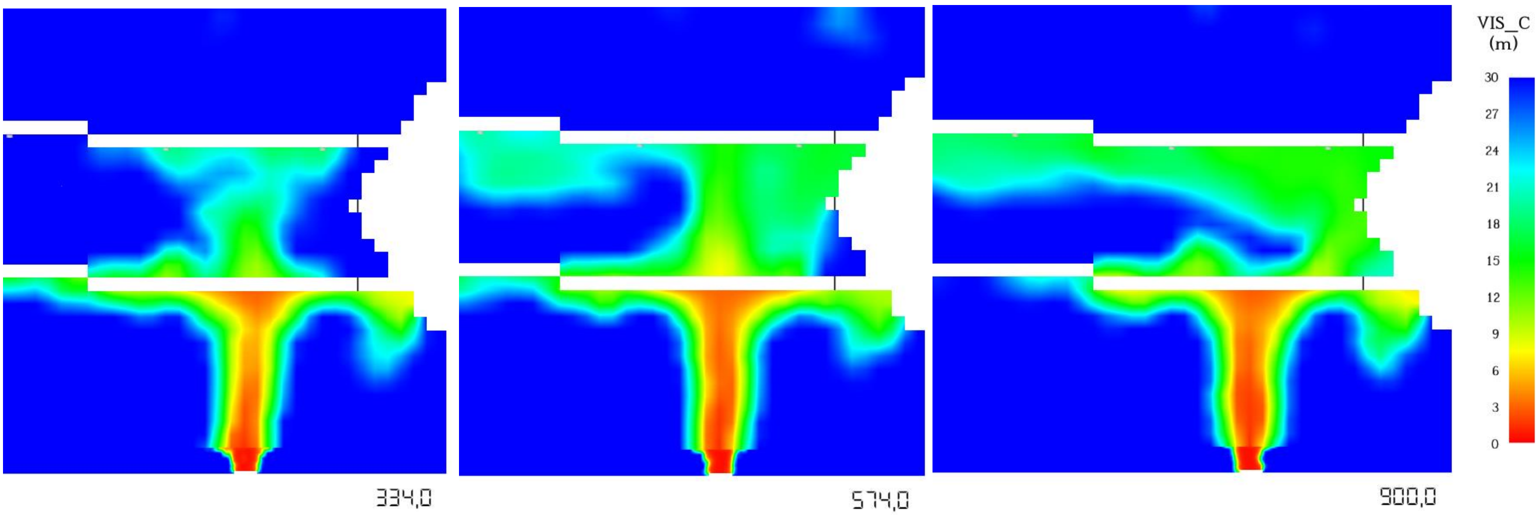


Fig.4.11. Visibility contour for scenario 3, at t=334, 574 and 900 s.

Scenarios 4 and 5 behave quite similarly to scenarios 1 and 2 respectively. Due to a larger pool diameter, it has taken more time for the pressurization system in both cases, to improve the visibility inside the loading walkway. For both cases, after one minute of functioning after activation there is already a clear improvement in visibility conditions. Nevertheless, for scenario 4 the reduced visibility is still very present, with large areas with a visibility around 12 m. However, after 4 minutes of functioning visibility has completely reached normal 30 m levels. For scenario 5, the improvement has been faster, as expected and after only one minute and a half visibility seemed to be normal again.

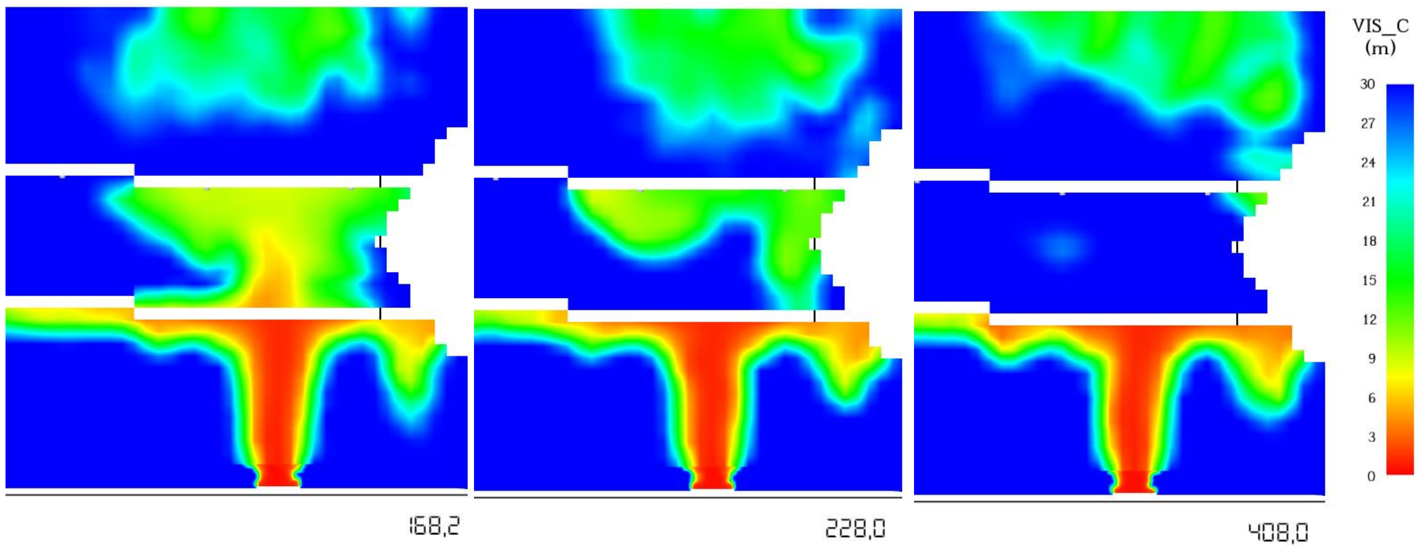


Fig.4.12. Visibility contour for scenario 4, at t=168, 228 and 408 s.

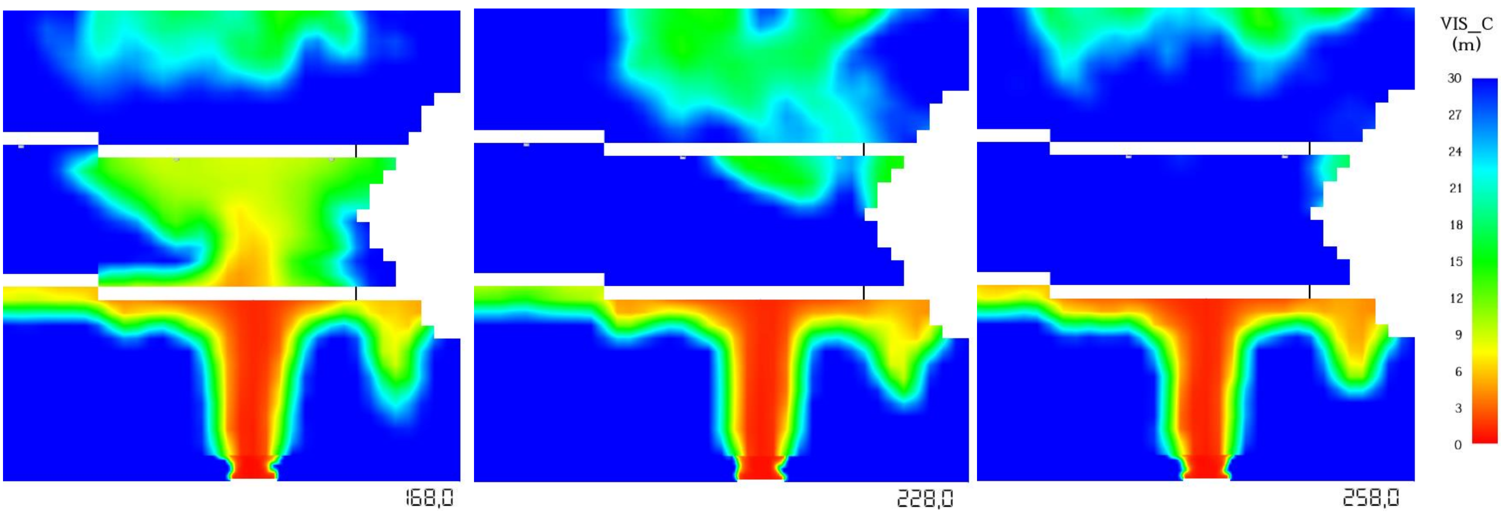


Fig.4.13. Visibility contour for scenario 5, at t=168, 228 and 258 s.

However, scenario 6 visibility contours show once again the flaws in a natural ventilation system. As in scenario 3, the ventilation system, rather than drive out the smoke and improve visibility, it only spreads the fumes and the areas where the visibility is reduced. The bigger diameter in this scenario only emphasizes this behavior, as visibility only gets worse after activation. At activation, various areas have visibility levels around 6 m but as time passes, these areas get bigger, and visibility is reduced to around 3 m at the end of simulation (t = 900 s). At this time, reduced visibility has spread to the two neighboring compartments.

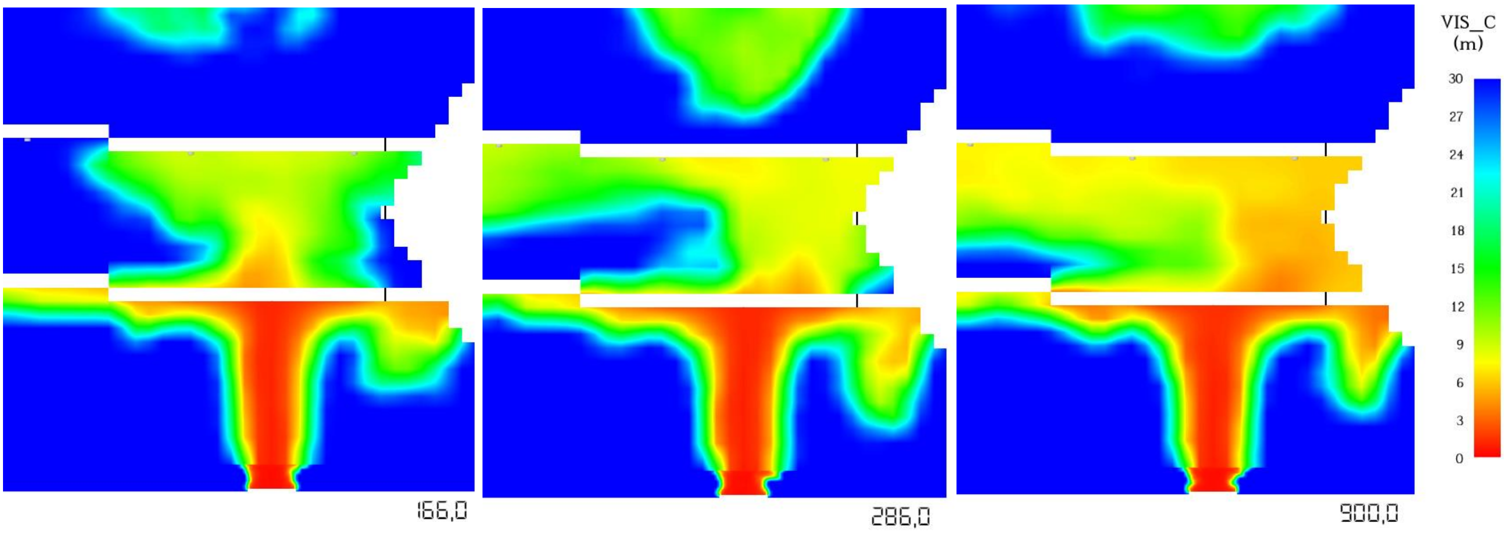


Fig.4.14. Visibility contour for scenario 6, at t=166, 286 and 900 s.

Just as natural ventilation shows its flaws at maintaining a tenable visibility inside the loading bridge, the pressurization system displays again, through scenarios 7 and 8, its effectiveness. Even with a pool diameter of 1,5 m, the pressurization system with an airflow of 3000 m^3/h (scenario 7) was able to significantly improve visibility in just one minute, with only minor areas having reduced visibility. Furthermore, even if these areas still had reduced visibility, it still was above the 10 m limit. After two and half minute, visibility was completely recovered. Also, in line with expectations, scenario 8 displayed a similar behavior but with a faster response. As airflow was increased to 9600 m^3/h in scenario 8, it took only one minute and fifteen seconds to completely recover the normal 30 m visibility inside the loading walkway.

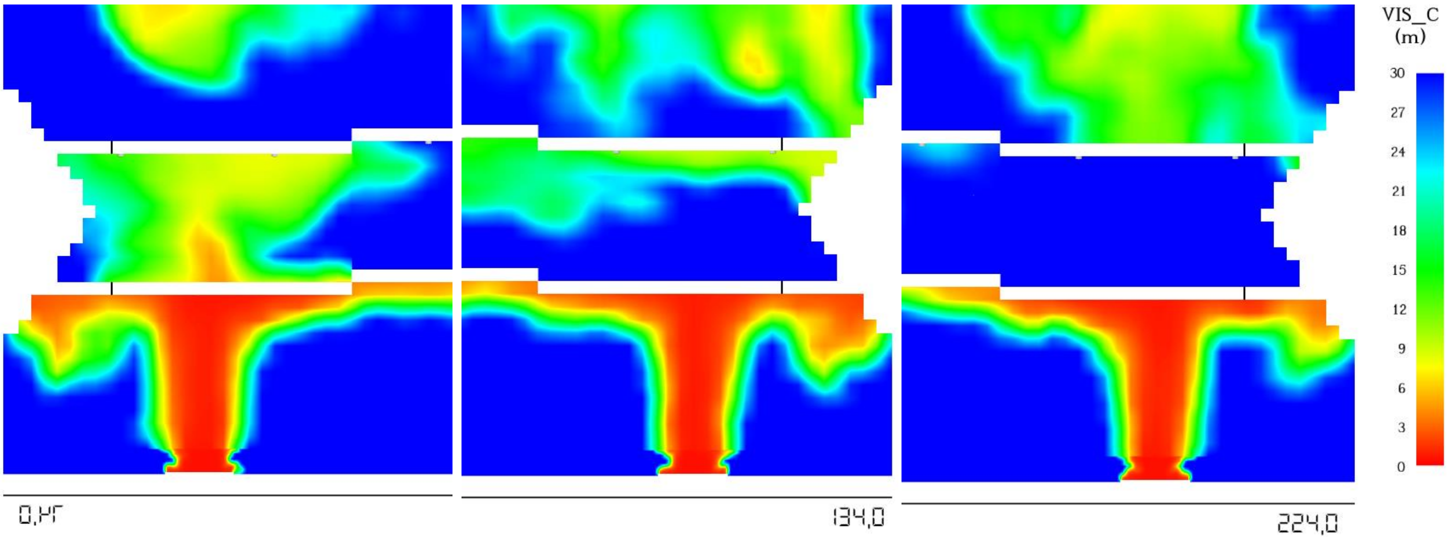


Fig.4.15. Visibility contour for scenario 7, at t=74, 134 and 224 s.

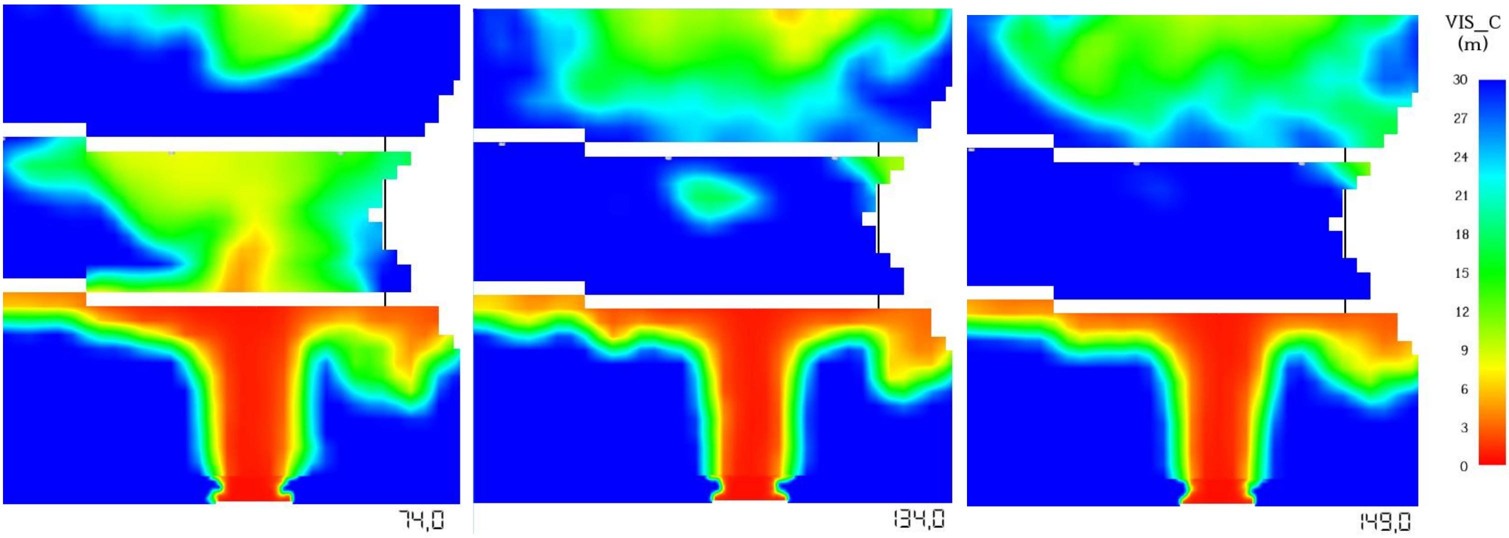


Fig.4.16. Visibility contour for scenario 8, at t=74, 134 and 149 s.

Regarding scenario 9, the system behaved just as in scenarios 3 and 6, but with more acute values. As the pool diameter was 1,5 m, bigger than before, the system struggle even more to contain the visibility drop. In this scenario, the situation was completely untenable, with visibilities around 0-3 m in most areas, even in other compartments.

4.3.3.3. Velocity contours.

Apart from maintaining a tenable environment as per NFPA standards, an important secondary objective is to try to achieve a comfortable environment for humans. For that reason, it is also crucial to analyze the air velocity inside the loading walkway, as it is an important factor for achieve a comfortable environment for human use. Therefore, the velocity contours will be assessed for the scenarios, these will help us determine if a comfortable environment was achieved.

As air velocity mainly relies on the type of system and the airflow, the contours will be grouped with these criteria. First, the contours of scenario 1,4 and 7 will be analyzed for their 3000 m^3/h. Secondly, scenarios 2,5 and 8 will be studied and finally the natural ventilation ones (3,6 and 9). Additionally, it is important to point out that the velocity contours analyzed correspond to the situation after the activation as before the activation, air velocity is practically zero. Also, as the air flow is turbulent, there is not a constant steady state. Nonetheless, variations are not too significant. As such, it has been assumed that after two minute of activation, steady state is achieved, and values can be considered at that time.

As such, for scenarios 1, 4 and 7, the following velocity contours have been obtained:

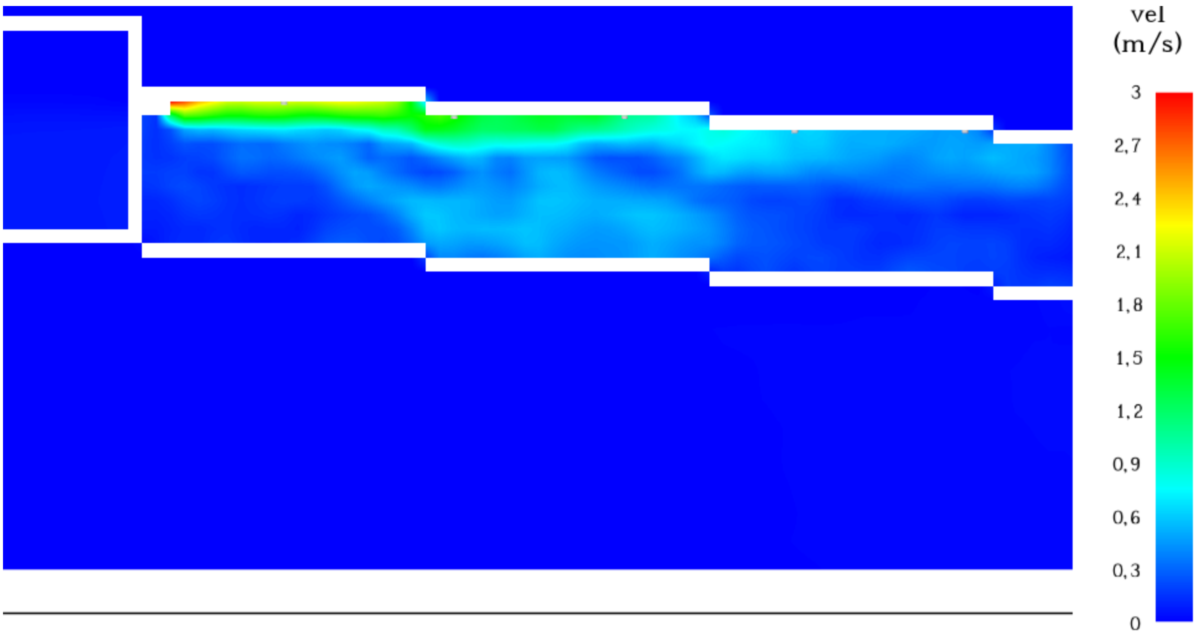


Fig.4.17. Velocity contour for scenario 1.

As displayed in the velocity contour, there are some areas, especially next to the HVAC's vent, where air velocity is higher than usual with values around 1,5 m/s. It is quite expectable to have a peak in velocity right next to the vent. The air flow values were calculated to have comfortable velocity for a cross area equivalent to the loading walkway's tunnel. Nonetheless, at the

HVAC's outlet, cross section is much narrower and as such, it causes a peak in velocity which later dissipates as air travels inside the tunnel. Even if the values around the outlet are far from comfortable, as they more less triple the comfortability threshold (0,5 m/s), the rest of the walkway has more acceptable and comfortable values in between 0 and 0,3 m/s. Hence, it can be concluded that for scenarios 1,4 and 7, air velocity is acceptable as in the far majority of the volume, the values obtained are under the threshold.

Nonetheless, the situation is different for a superior air flow as in scenarios 2,5 and 8, as shown in Fig.4.20, displaying the contour for scenario 2 after two minutes from activation. In this case, velocity near the HVAC's outlet is too high, exceeding the threshold by 6 times with values as high as 3 m/s. Additionally, these high speeds take more distance to be reduced. In the two first compartments, about 6 m in total, air speeds average around 1,5 m/s, three times the limit, and in the other two following, the speed is still exceeding as it is around 0,6 m/s. As such, during the first 12 m of the tunnel, the comfortability threshold seems to be exceeded almost everywhere. Nonetheless, at the end of the tunnel, air velocity is acceptable around 0,3 m/s. Thus, it has to be noted that to employ such high air flow, a different vent will need to be used as the outlet's velocity is far from acceptable limits, even if downstream values are valid.

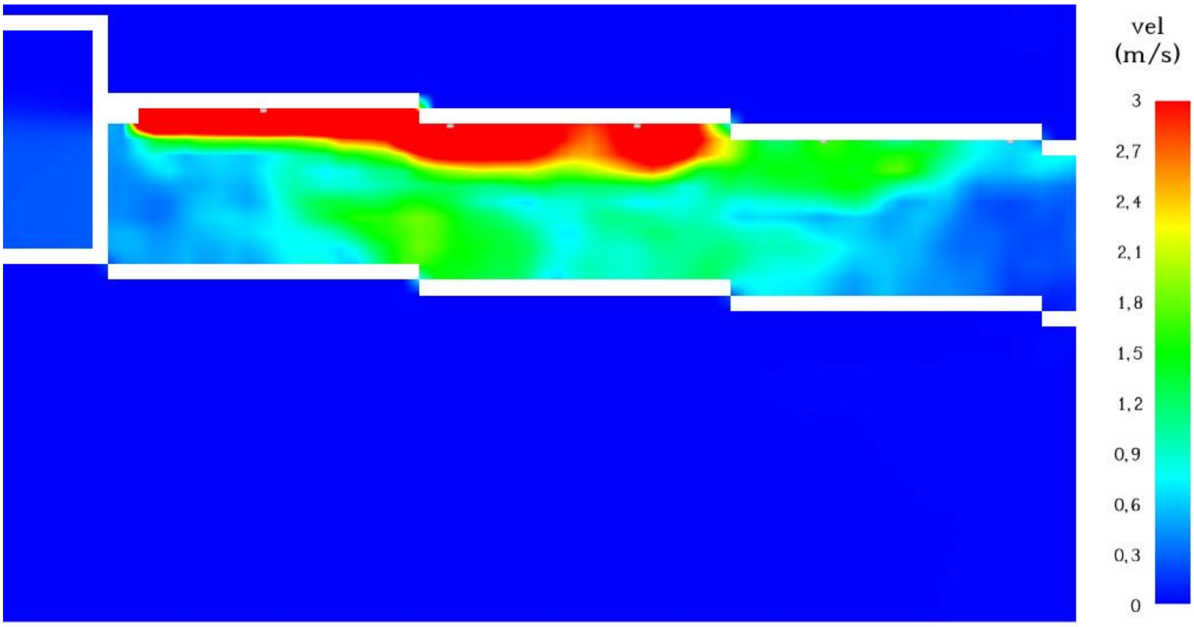


Fig.4.18. Velocity contour for scenario 2.

On the contrary to the pressurization cases, for the natural ventilation ones, air velocity is not an issue. The results are expectable as no device moves mechanically the air in natural ventilation systems, but rather the air is moved and ventilated through buoyancy and convection associated with thermal differences. As such, in natural ventilation, air speeds are usually very low, which is exactly the case for scenarios 3, 6 and 9 in which we obtain values around 0 and 0,3 m/s.

4.3.4. Smoke sensors, CO and CO_2 presence and mean temperature.

The main results of the simulation have been detailed data on each smoke detector output, mean temperature, mean CO and CO2 presence during the whole 900 s of simulation. This data provides an important insight into the evolution of crucial variables for the jet bridges environment and its tenability and comfortability. Hence, providing key information to evaluate the validity of the protection systems.

4.3.4.1. Smoke detectors output.

After each simulation, detailed information on the smoke detectors value have been analyzed. There is a collection of values, approximately one value for each of the 15 detectors every half second. These values are expressed as %/m, meaning the percentage of visibility lost for each meter of smoke with that density.

As the results have been obtained at specific points, it is difficult to calculate the exact loss of visibility as this value depends on the geometric point it is measured. Nonetheless, to estimate the visibility range and the percentage of visibility lost, the approximation made is to evaluate the geometrical mean between two neighbor smoke detectors, which are distanced by three meters. As such, we obtain:

$$v_{mean} = \frac{v_i + v_{i+1}}{2}$$

$$V = V_{normal} - \frac{V_{normal} \cdot v_{mean} \cdot L}{100}$$

v_i *is the visibility loss of smoke detector i* $(\frac{\%}{m})$

v_{i+1} *is the visibility loss of smoke detector* $i + 1$ $(\frac{\%}{m})$

v_{mean} *is the mean visibility loss between smoke detectors i and* $i + 1$ $(\frac{\%}{m})$

L *is distance between detectors*, $3\ m$

V_{normal} *is the normal visibility inside the jet bridge*, $30\ m$ *in this case*

V *is the actual visibility* (m)

For scenario 1, the following results have been obtained for the smoke detectors:

Smoke detector Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum Value (%/m)	2,8493746	6,854328	0	0	0	0	0	0	0	0	0	0	0	0	0
Max average Visibility Loss (%/m)	5,5499056														
Lowest visibility (m)	25,005085														

Table 4.9. Visibility loss and lowest visibility for scenario 1 before system activation.

Smoke detector Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum Value (%/m)	13,272952	14,175656	0,0004494	0,0004461	0,0002488	0,0002279	0,0002141	0,0002151	0,00015	8,816E-05	4,694E-05	2,52E-05	2,293E-05	1,63E-05	4,426E-06
Max average Visibility Loss (%/m)	11,838231														
Lowest visibility (m)	19,345592														

Table 4.10. Visibility loss and lowest visibility for scenario 1 after system activation.

Fig.4.19. Visibility loss for scenario 1.

As shown tables 4.9 and 4.10, the lowest visibility reached for this scenario is 19,35 m which is superior to the minimum visibility criteria of 10 m. Hence, the protection system complies with this criterion in this case. Nevertheless, it is interesting to point out this lowest visibility value is reached after the activation of the pressurization system. Here, the graphic evolution of the smoke detectors output is helpful, as it shows in fig.4.22. there is a certain inertia in the system: it takes some time after the activation for visibility values to start dropping until they are finally negligible.

For scenario 2, results are very similar. The most notorious difference is that values are a little inferior to the scenario 1 results, which is logical as the air flow has been increased.

Smoke detector Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum Value (%/m)	2,8493731	6,85432	0	0	0	0	0	0	0	0	0	0	0	0	0
Max average Visibility Loss (%/m)	5,7121097														
Lowest visibility (m)	24,859101														

Table 4.11. Visibility loss and lowest visibility for scenario 2 before system activation.

Smoke detector Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Maximum Value (%/m)	13,464135	14,672	0,00042	0,00033	0,00034	0,00021	0,0002	0,0002	9E-05	8E-05	2E-05	2E-05	2E-05	1E-05	5E-06
Max average Visibility Loss (%/m)	11,222125														
Lowest visibility (m)	19,900087														

Table 4.12. Visibility loss and lowest visibility for scenario 2 after system activation.

Even if smoke and visibility behavior is very similar in scenarios 1 and 2, this is not the case for scenario 3, in which natural ventilation is employed. The lowest visibility for this case is also achieved after activation and is above the minimum criteria, being 14,18 m. Nonetheless, this is not due to the fact that after activation, some time is needed to reduce smoke and recover visibility but rather that the system is ineffective. After activation, visibility values do not recover but are more or less maintained as shown by Fig.4.23. presenting visibility loss variation in time for each detector.

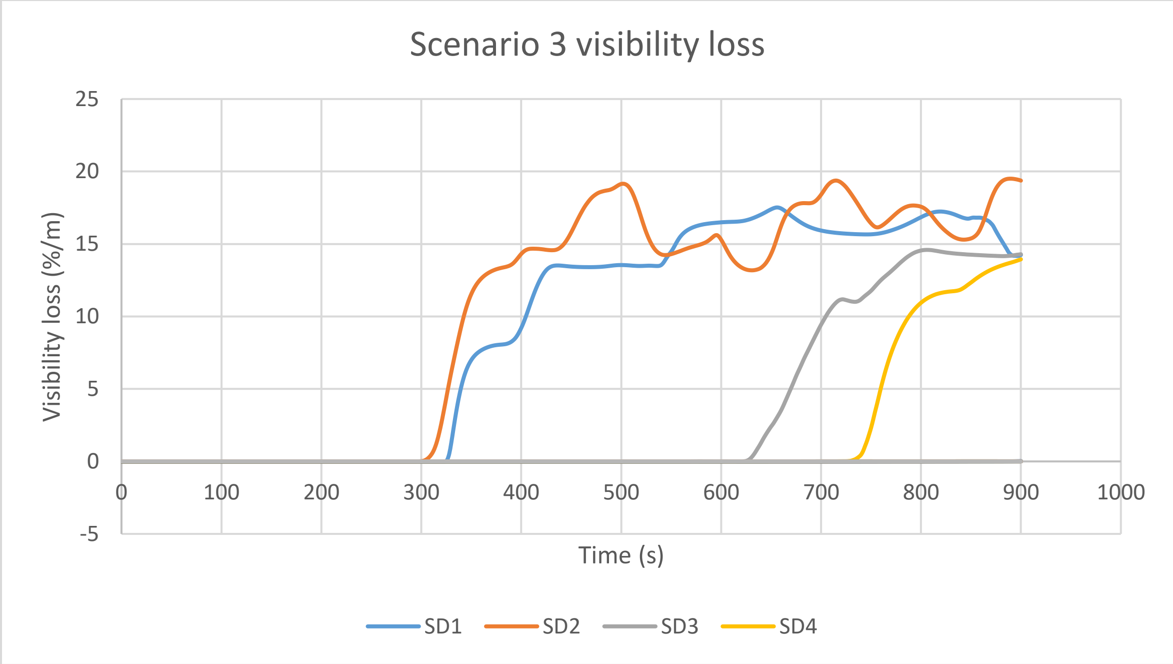


Fig.4.20. Visibility loss for scenario 3.

		Before activation		After Activation	
		Max average visibility loss (%/m)	Min visibility (m)	Max average visibility loss (%/m)	Min visibility (m)
Scenario	1	5,56	25,01	11,84	19,35
	2	5,712	24,86	11,222	19,9
	3	4,496	25,953	17,574	14,183
	4	27,096	5,614	16,65	15,02
	5	24,89	7,601	7,4	24,34
	6	34,307	0	38,244	0
	7	27,455	5,29	8,564	22,29
	8	27,608	5,153	0,123	29,89
	9	36,902	0	44,28	0

Table 4.13. Visibility results summary.

For scenario 4, behavior is different to the previous ones. The lowest visibility values are achieved before activation of the pressurization system. After the activation, visibility levels quickly recover and at the end of the simulation visibility has fully reached normal levels. Nonetheless, the lowest visibility achieved is 5,61 m which is noticeably under the 10 m criteria. In this case, the system is effectively driving the smoke outside and maintaining a tenable environment. Nevertheless, activation of the system happens to late for the visibility to be above the threshold at all times. As such, even if the pressurization system acts correctly, it is activated too late.

In the case of scenario 5, behavior is very similar to scenario 4. The main difference between them is that minimum visibility is improved from 5,61 m to 7,60 m previous to the activation, and from 15,02 m to 23,34 m after.

On the contrary, scenario 6 is unsimilar to 4 and 5. As previously seen in scenario 3, the natural ventilation system is not able to bring visibility values back to normal. This issue has increased in scenario 6 as visibility level are down to 0 both before and after activation. After this scenario, it can be concluded that natural ventilation is not fitted for these types of situations.

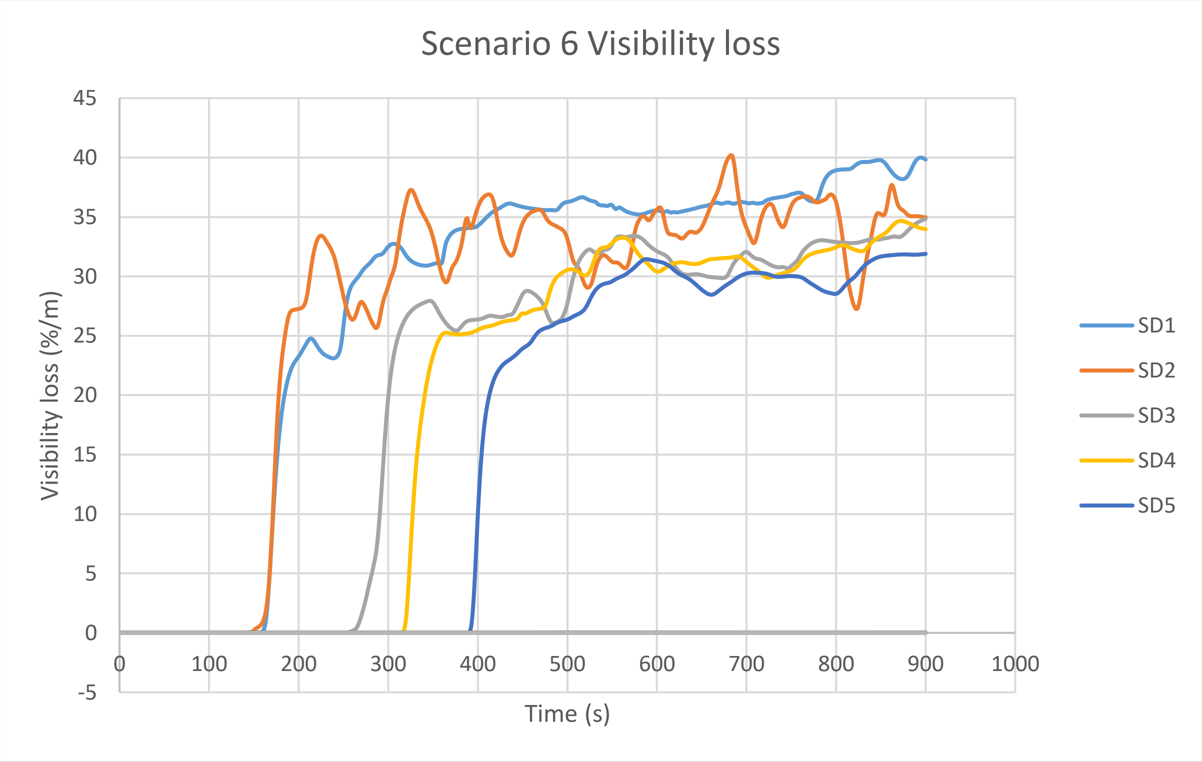


Fig.4.21. Visibility loss for scenario 5.

In line with the previous pressurization scenarios, particularly scenarios 4 and 5, visibility for cases 7 and 8 falls under the 10 m criteria before activation (5,29 m and 5,15 m respectively) but after the pressurization is activated, visibility levels are almost recovered and are well above the 10 m criteria (22,29 m and 29,89 m respectively).

As scenario 7 and 8 are similar to the rest of cases where pressurization systems are used, the same happens for the natural ventilation ones and scenario 9. As in case 6, not only does the protection fails to recover visibility levels but visibility continues to drop down. As such, before and after activation visibility levels reach 0 m.

Regarding the visibility criteria, it can be clearly concluded that natural ventilation is clearly ineffective and can be discarded as a protection system to maintain a tenable environment for any exterior pool fire superior to 0,5 m in diameter. On the contrary, pressurization systems have been proved very effective maintaining visibility for any pool diameter. The pressurization system has been tested with air flows of 3000 m^3/h and 9800 m^3/h and have maintained a tenable visibility even with the lower air flow of 3000 m^3/h, even for 1,5 m pool diameter. Nonetheless, in scenarios 4,5, 7 and 8 visibility levels have fallen under the 10 m threshold before activation. As such, it can be concluded that the pressurization system is only effective if activation comes at the right time and as such, the activation procedure needs to be improved in order for the system to start working earlier for visibility levels to not drop under 10 m in any case.

4.3.4.2. CO presence.

As stated in section 4.4.1 of this study, the estimation of how long passengers stay inside the loading walkway during an evacuation is 45 s if visibility is higher than 3 m and 150 s if this is not the case. Nevertheless, in table 4.6 there are no values under 4 mins to estimate the tenability of the environment in terms of CO presence. As such, the 4 min criteria will be used as it is the lowest and nearest to our estimated value and it is more restrictive. Using the 0,3 criteria as previously explained for a 4 min time, the fractional dose of CO (FED_{CO}) will have to be under 1706.

Hence, having established the CO threshold, the fractional doses for each scenario have been compiled in the following table. It is important to note that the fractional dose has a 35 % of uncertainty therefore, the interval around the obtained value will be used.

Scenario	1	2	3	4	5	6	7	8	9
FED_{CO} obtained	0,0103	$5,79\cdot10^{-3}$	0,0569	0,0204	$8,49\cdot10^{-3}$	0,192	0,0330	$8,33\cdot10^{-3}$	0,253
FED_{CO} interval	[$6,70\cdot10^{-3}$; $1,39\cdot10^{-2}$]	[$3,77\cdot10^{-3}$; $9,56\cdot10^{-3}$]	[$3,70\cdot10^{-2}$; $7,68\cdot10^{-2}$]	[$1,33\cdot10^{-2}$; $2,75\cdot10^{-2}$]	[$5,52\cdot10^{-3}$; $1,15\cdot10^{-2}$]	[0,125; 0,317]	[$2,15\cdot10^{-2}$; $5,45\cdot10^{-2}$]	[$5,41\cdot10^{-3}$; $1,12\cdot10^{-2}$]	[0,164; 0,341]

Table 4.14. Fractional dose of CO obtained in each scenario.

It can be concluded regarding CO presence, that the protection system does work very effectively in containing CO as in no scenario was the threshold surpassed. The highest dose obtained was 0,341, very far from the limit of 1706.

4.3.4.3. CO_2 presence.

As stated, the criteria used for assessing safe levels of CO_2 inside the loading walkway will be a CO_2 concentration inferior to 30.000 ppm. As such, the following table presents the average concentration of CO_2 for each scenario:

Scenario	1	2	3	4	5	6	7	8	9
CO_2 concentration (ppm)	449	421	731	510	438	1551	586	437	1917

Table 4.15. Concentration of CO_2 for each scenario.

As seen, all the scenarios are in compliance with the CO_2 criteria. Also, in line with the visibility results and CO presence, all the natural ventilation scenarios (3,6 and 9) seem to perform less effectively.

4.3.4.4. Mean temperature.

As previously discussed, room temperature is an important factor regarding human comfort and should be controlled within a specified bracket. One the important data outputs of each simulation have been the instantaneous mean temperature in the loading walkway. As such, this data has been compiled in Table 4.18 with the maximum instantaneous mean temperature and the average mean temperature along the 900 s of simulation, for the 9 scenarios.

Scenario	1	2	3	4	5	6	7	8	9
Max mean temperature (ºC)	20,02	20,10	20	20,03	20,11	20,04	20,34	20,48	20,76
Average mean temperature (ºC)	20,01	20,03	20	20,02	20,04	20,03	20,10	20,06	20,58

Table 4.16. Maximum and average mean temperatures for each scenario.

According to ASHRAE Standard 55 [6], room temperature must be equal or less than 26 ºC for human comfort. As per the results, all values are very close to the ambient 20 ºC as it seems the loading walkway has worked as good thermal insulator and as effectively protected the interior of the jet bridge from high heat. Hence, from the thermal point of view, it can be concluded that comfort has been maintained in every scenario.

4.3.5. Results summary.

4.3.5.1. Tenability results summary.

The criteria selected to be able to confidently state that the environment is tenable are:

· Visibility of at least 10 m.

· Limited CO exposure.

· Limited CO_2 exposure.

To summarize the behavior of the systems for each of these criteria, Table 4.19 has been created. Here is displayed if each of the systems (pressurization for 3000 m^3/h, pressurization for 9800 m^3/h) has complied with the criteria for each of the scenarios.

	Pool Diameter (m)	Visibility criterion	CO criterion	CO_2 criterion
Pressurization 3000 m^3/h	0,5	YES	YES	YES
	1	YES	YES	YES
	1,5	YES	YES	YES
Pressurization 9800 m^3/h	0,5	YES	YES	YES
	1	YES	YES	YES
	1,5	YES	YES	YES
Natural Ventilation	0,5	YES	YES	YES
	1	NO	YES	YES
	1,5	NO	YES	YES

Table 4.17. Compliance with tenability criteria for each protection system.

In light of the results, it is clear the most difficult criterion to comply with is visibility. Not only every system complied with the CO and CO_2 criteria, but the values obtained were also very far from the specified threshold. Regarding visibility, protection system struggled more to comply with it. In this regard, natural ventilation appeared to be completely ineffective as it only could comply for a pool diameter of 0,5 m. Nonetheless, it has to be noted that the pressurization system, specially for the reduced airflow, did struggle to recover visibility for the last scenario.

It is also interesting to note that for pool diameters of 1,5 m, the loading walkway faced the possibility of structural collapse, a situation for which pressurization system should not be designed. However, for both air flow values, the pressurization system managed to comply with the criteria.

Finally, it is important to note that even if these systems managed to ensure a tenable environment once activated, the environment was not in a tenable condition before that event. As such, the best option is to employ this system with a much faster and reactive activation system to ensure that a tenable environment is maintained at all times.

4.3.5.2. Comfort results summary.

As for the tenability conditions, there are also clear comfort conditions, which are part of an important secondary objective of this study. These are:

· Temperature under 26 ºC.

· Air speed under 0,5 m/s.

As in the previous section, the compliance with the comfort criteria for each system has been summarized in table 4.20.

	Pool Diameter (m)	**Temperature criterion**	**Air speed criterion**
Pressurization 3000 m^3/h	0,5	YES	YES
	1	YES	YES
	1,5	YES	YES
Pressurization 9800 m^3/h	0,5	YES	NO
	1	YES	NO
	1,5	YES	NO
Natural Ventilation	0,5	YES	YES
	1	YES	YES
	1,5	YES	YES

Table 4.18. Compliance with comfortability criteria for each protection system.

Comfort temperature has not been the issue in any of the cases, as temperatures were very close to the original 20ºC. Nevertheless, that has not been the case for air speed. Even if air flow was calculated to maintain air speed under 0,5 m/s, due to the reduced outlet of the HVAC, air is introduced to the tunnel at a higher speed. This is not much of a problem for an air flow of 3000 m^3/h as flow rapidly spreads to the whole tunnel section and slows down to comfort speed values. Nonetheless, an air flow of 9800 m^3/h is too high and the distance it takes the flow to slow down is too big as in some areas the comfort limit was exceeded even by 6 times.

Chapter 5: Conclusions.

5.1. Objectives assessment.

The original objective of this study is to respond to the needs laid out in NFPA 415 [1] and provide a solution to the issue at hand: a protection system that will be able to protect passengers during an egress situation from the fumes and smoke from an outside fuel fire. Not only, was it necessary to think about system that could accomplish the task of NFPA 415 [1], but also to assess the capabilities and performance in this type of situation to maintain a tenable and comfortable environment.

As such, a thorough study of the situation has been performed. A review of the type of incidents that usually occurred has been necessary to identify properly the situation, to focus on pool fuel fires. Hence, a proper analysis of pool fires and their behavior was executed, along with the identification and analysis that could define with accuracy the type of situation for which the protection system had to be effective. Thanks to this analysis, a model could be created in order to test the selected protection systems (natural ventilation and pressurization for 3000 m^3/h and 9800 m^3/h) and assess with confidence their performance for three different pool fires situation.

After assessing the results obtained, it can be confidently stated that natural ventilation is not an option. It could have been the most optimal solution due to its low cost, maintenance, and consumption. Nonetheless, it could not keep up with one of the three crucial tenability criteria, as for any pool diameter superior to 0,5 m tested, it was able to maintain a visibility of at least 10 m. Furthermore, visibility is key as a low visibility will lead to slower evacuation and as such, more exposure to danger and the other two tenability criteria, CO, and CO_2 exposure.

On the contrary, a pressurization system performed adequately, managing to comply to all tenability criteria for both of the air flows tested, 3000 and 9800 m^3/h. This system even managed to comply with the criteria for the 1,5 m diameter pool, which represents a situation in which structural integrity is at risk due to high exterior temperatures and for which a system of this sort is not expected to perform. Nonetheless, this system appeared to have some issue to comply to comfort criteria, specifically with an air flow of 9800 m^3/h. Due to the small HVAC outlet, flow was accelerated enough to reach velocities six times faster than the comfort limit. Nonetheless, as the system was able to perform with only a 3000 m^3/h, it is recommended here to employ a pressurization system with this air flow, as it will be able to maintain a tenable environment, as well as comfort and be more economical than one with a higher air flow.

Finally, it is important to note that this pressurization system must be reliant on a good and measured activation system. As reviewed previously, the activation system used in this study was too slow to be able to maintain a tenable environment at all times. Hence, it is recommended that a study is done in order to assess the best way to active the protection system.

5.2. Future improvements.

Due to the limited time in this project, the scope had to be bounded. As a result, various hypotheses and simplifications where made, as well as some areas were not included in the scope of the project. Hence, there is room for future improvements, such as:

· Analysis of other type of incidents as seen in the literature review, pool fires and fuel spills were not the only cause of fires in airports. As such, it would also be interesting to perform the same study for other sources of fire, such as electrical fires, in order to test the pressurization system against these.

· Simplifications: Many simplifications have been made. For a further study, there is room to improve the geometrical model of the loading walkway, including for details that were omitted such as doors and stairs. Additionally, the HVAC for the pressurization system is also greatly simplified and a more detailed model would be beneficial for more accurate trustworthy results. Finally, n-dodecane was chosen to model jet fuel nevertheless, jet fuel is much richer and complex in different components. Thus, a more thorough fuel model could be considered for improvement.

· Flame impingement: Through a preliminary analysis it was obtained than for diameters bigger than 1,5 m, flame impingement could happen and thus, compromising the structural integrity of the loading walkway. Nonetheless, after analysis of the simulation's results it appeared that with that diameter, temperatures could already cause a structural failure. By finding exactly the minimum diameter for which the structure is compromise can help significantly design the pressurization system in order to not over design it and achieve a more efficient solution.

· Air flow: As per the results, a 3000 m^3/h air flow is able to maintain both a tenable and comfortable environment. Nevertheless, it is possible that a lower air flow could achieve the same but being a more efficient solution. Therefore, it would be interesting to find the limit air flow for which tenability and comfort conditions are not met.

Chapter 6: References.

[1] National Fire Protection Association, Standard on Airport Terminal Buildings, Fueling Ramp Drainage, and Loading Walkways, NFPA 415, 2022.

[2] International Air Transport Association, Safety Report 2019, Edition 56, April 2020.

[3] United Nations General Assembly, 70th session, The 2030 agenda for sustainable development, September 25th, 2015.

[4] Joshua D. Swann, Joseph L. Scheffey, Hughes Associates, Fire Protection Research Foundation, Aircraft Loading Walkways – Literature and Information Review, May 2014.

[5] National Fire Protection Association, Standard for Smoke Control Systems, NFPA 92, 2021.

[6] American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), ANSI/ASHRAE 55-2017 – "Thermal Environmental Conditions for Human Occupancy", 2017.

[7] International Organization for Standardization (ISO), ISO 7730:2005: Ergonomics of the thermal environment, 2005.

[8] American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), Handbook of Smoke Control Engineering, 2007.

[9] C. Goula, C. Malkotsi, Numerical simulation of pool hydrocarbon fires and their effect on adjacent tanks, Thessaly, 2017.

[10] B. Rengel, C. Mata, E. Pastor, J. Casal, E. Planas, A priori validation of CFD modelling of hydrocarbon pool fires, Barcelona, 2019.

[11] Ian M. Kennedy, Models of Soot Formation and Oxidation, Davis, 1997.

[12] Chevron Products Company, Aviation Fuels Technical Review, San Ramón, 2007.

[13] Serban C. Moldoveanu, Pyrolysis of Organic Molecules: Applications to Health and Environmental Issues, 2019.

[14] American Society for Testing and Materials (ASTM), Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM E119, 2022.

[15] M. Muñoz, J. Arnaldos, J. Casal, E. Planas, Analysis of the geometric and radiative characteristics of hydrocarbon pool fires, Barcelona, 2004.

[16] National Fire Protection Association (NFPA), National Fire Alarm and Signaling Code, NFPA 72, 2022.

[17] Society of Fire Protection Engineers (SFPE), K. Fridolf, WSP Sverige AB D. Nilsson, H. Frantzich, E. Ronchi, S. Arias, Walking Speed in Smoke: Representation in Life Safety Verifications, Lund University.

[18] Occupational Safety and Health Administration (OSHA), Carbon Dioxide Health Hazard Information Sheet.