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NUMERICAL STUDY ON THE INFLUENCE OF THE ATMOSPHERIC WIND IN THE FIRE DYNAMICS AND HEAT TRANSFER IN A COMPARTMENT FIRE

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Abstract. *Although wind conditions are acknowledged to influence significantly fire dynamics and enhance the external fire spread in urban and wildland fires, still little work and research has been made to comprehend the effect of external wind conditions in fire dynamics and fire spread in urban fires. This study aims to analyze the effect of the atmospheric wind in the fire dynamics and heat transfer in a post-flashover compartment fire. A series of numerical experiments was conducted through a CFD code namely Fire Dynamic Simulator (FDS) for a full-scale ISO 9705 room for different wind speeds (0 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s and 25m/s), wind directions (side wind and back wind) and compartment boundary characteristics (thermally-thin and thermally-thick). A mesh resolution analysis was performed to ensure the quality of the numerical results. Additionally, the numerical model was validated comparing the obtained results to under-ventilated, post-flashover compartment fire experimental data available in the literature, showing a good agreement. The study showed that both, wind speed and direction can affect significantly the wall and hot gas temperatures, and also the heat fluxes through the compartment walls. For a constant heat release rate (HRR), the average windward wall (internal and external) temperatures and the hot gas temperatures were inversely proportional to the wind speed. It was also observed that thermally-thin and thermally-thick compartments are affected differently by the atmospheric wind, the thermally-thin presenting more uniform gas temperature profiles and having their net wall heat fluxes more affected by the wind.*

Keywords: *fire dynamics, heat transfer, atmospheric wind, post-flashover, under-ventilated compartment fire*

1. INTRODUCTION

Some historical large scale urban fires, such as the Great London Fire (1666), the Great Chicago Fire (1871), The San Francisco Fire (1906), and more recently the Valparaíso (2014) and Imizamo Yethu (2017) informal settlement fires happened under severe wind conditions. These wind conditions, such as wind speed and direction are acknowledged to influence significantly fire dynamics and enhance the external fire spread in urban and wildland fires. However, still little work and research has been made to comprehend the effect of external wind conditions in fire dynamics and fire spread in urban fires.

The Imizamo Yethu informal settlement fire occurred in Cape Town, South Africa on 11 March 2017, causing 4 deaths, destroying 2194 informal dwellings and displacing over 9700 people (Kahanji *et al.*, 2019). According to Kahanji *et al.* (2019), both, the wind speed and direction affected significantly the fire spread within the informal settlement. The rate of fire spread was boosted by the wind speed, pushing the fire fronts to engulf unburned combustible materials.

It is estimated that nowadays, more than one billion people live in informal settlements (favelas, ghettos, slums, etc.) around the world, most of them in developing countries. South African informal settlement dwellings are often constructed from readily available materials, such as wood frames cladded with corrugated roof sheeting (steel/asbestos). Dwellings cladded with steel sheets present characteristics of thermally-thin compartments, while those cladded with asbestos cement sheets or made of bricks have the characteristics of thermally-thick compartments. According to Centeno *et al.* (2020) thermally-thin bounded compartments are commonly found in South African informal settlements, while thermally-thick bounded compartments are seen in Latin American and South East Asian informal settlements.

To study the influence of the dwelling boundary on the development and spread of fires in informal settlements, Wang *et al.* (2020) conducted four real-scale experiments. They found that the boundary conditions in informal settlement significantly affect the fire dynamics and fire spread, and that current analytical/empirical equations (e.g.

maximum gas layer temperature and neutral plane height) do not capture accurately experimental observations.

As an effort to predict the onset of flashover in thermally-thin compartment fires, Beshir *et al.* (2020) conducted small-scale experiments and numerical simulations (FDS models) to determine the HRR required for reaching the onset of flashover in thermally-thin under-ventilated compartments. They developed a semi-empirical correlation to predict the HRR necessary for reaching flashover in this type of compartments. Centeno *et al.* (2020), continued the work of Beshir *et al.* (2020) and investigated the effect of wind on the heat release rate required to reach the onset of flashover. The study was carried through numerical simulations (FDS models) in small-scale thermally-thin and thermally-thick compartments in a wind tunnel. They found that HRR required for flashover increased with wind velocity for thermally-thin compartments, while it decreased for thermally-thick compartments. They concluded that those results were caused by heat transfer losses through walls and by wind-induced pressures at the doorway, the former being the driving mechanism for thermally-thin compartments and the later for thermally-thick compartments.

Beshir *et al.* (2021) employed FDS to model and validate four under-ventilated thermally-thin compartment fire tests with different wall boundary conditions. Using this validated FDS model, they developed a new flashover criteria for thermally thin compartments, once they observed that the gas layer temperature needed to reach flashover ranged between 360 °C and 460°C, in comparison to the well-known 525 °C and 600 °C flashover criteria for thermally-thick compartments. They also proposed an empirical correlation to estimate the HRR required for the onset of flashover.

According to Pitts (1991), the mechanism of fire spread between adjacent structures is one of the principal factors which must be characterized in order to predict urban fire spread, although there is still serious uncertainties concerning the heat transfer processes responsible for this mechanism in no wind conditions, and very little attention has been given to fire spread in the presence of wind. Most of the studies concerning the wind effect in fire dynamics and fire spread available in the literature were conducted in reduced-scale models in wind tunnels.

Hu *et al.* (2017a) investigated experimentally through reduced-scale compartments with one opening, the temperature evolution inside the compartment, the transitions of fire growth from stratified phase to well-mixed phase and the critical conditions for flame ejection through openings. The flame ejection under the influence of wind was also investigated by other authors, such as Hu *et al.* (2017b), who studied the facade flame height ejected through an opening under different ventilation factors, HRR and wind speed and Li *et al*. (2017), who investigated the intermittent characteristic of the flame ejecting from the window (flame projection probability).

Ren *et al.* (2018) studied the temperature profile of the fire plume ejected through the opening of the compartment subjected to wind. Chen *et al.* (2008) and Huang *et al.* (2009) studied the wind effect on fire behavior in a compartment with two opposite openings (cross-ventilation). In both studies similar conclusions were made, they observed two contradictory effects caused by the wind on the compartment fire. The wind promoted an increase in the fire severity by supplying more oxygen and at the same time cooled the fire by additional heat losses and dilution of combustion products.

Although reduced scale wind tunnel experiments are a good tool to study the wind effect, these wind tunnels employed for fire studies generate uniform velocity profiles with low turbulence fluctuations, which do not correspond to the real characteristics of an atmospheric wind.

The present work aims to analyze numerically the effect of the atmospheric wind in the fire dynamics and heat transfer in a full-scale ISO 9705 compartment fire. Different wind speeds (0 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s and 25 m/s), wind directions (side wind and back wind) and compartment boundaries (thermally-thin and thermally-thick) were analyzed.

2. METHODOLOGY

A parametric study was conducted to analyze the influence of an atmospheric wind in the fire dynamics and heat transfer in a compartment fire. The numerical experiments were conducted through a CFD code namely Fire Dynamics Simulator (FDS) for a full-scale ISO 9705 room exposed to different wind speeds (0 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s and 25 m/s) and wind directions relatively to the compartment opening (side wind and back wind relative to the compartment opening placed at the front wall), also different compartment boundary characteristics (thermally-thin and thermally-thick) were considered. The numerical experiments (simulations) performed in the parametric study are summarized in Table 1.

FDS is a free and open source computational fluid dynamics (CFD) model, developed by the National Institute of Standards and Technology (NIST) and VTT Technical Research Center of Finland, which solves the fluid dynamics problem by solving the Navier–Stokes equations adapted to buoyancy driven low Mach numbers (Ma < 0.3), applying a second order scheme in time and space. In this study, the default FDS turbulence and combustion models were applied and the Radiative Transfer Equation (RTE) was solved through the Finite Volume Method (FVM) with a gray gas model. More information about the mathematical model solved by FDS can be found in McGrattan *et al.* (2020a).

2.1 Problem statement and numerical modeling

The geometry used in this parametric study is a full-scale standard ISO 9705 room (2.4 m (L) × 3.6 m (W) × 2.4 m (H)) with a doorway of 0.8 m (W) x 2 m (H) in the middle of the short wall (front wall), similar to the geometry of the validation case ISOHept4 described by Lock *et al.* (2008); the main differences are that in the present parametric study the compartment floor was placed at the ground level and the room wall properties were changed to represent steel (thermally-thin) and asbestos cement (thermally-thick) sheets, materials usually found in informal settlement dwellings. The thermal properties of the materials applied to the compartment solid boundaries in the parametric study were obtained from Drysdale (2011) and are conductivity ($k = 45.8$ W/(m·K)), specific heat ($c_p = 460\ \mathrm{J/(kg \cdot K)}$), density ($\rho = 7850\ \mathrm{kg}/m^3$) and thickness ($\delta = 0.5$ mm) for steel boundaries, and $k = 0.15$ W/(m·K), $c_p = 1050\ \mathrm{J/(kg \cdot K)}$), $\rho = 577\ \mathrm{kg}/m^3$ and $\delta = 13$ mm for asbestos cement boundaries. The boundary emissivity for both cases was assumed constant and equal to 0.9.

Table 1. Studied cases

Thermally-Thick walls (Asbestos cement)			Thermally-Thin walls (Steel)		
Wind Speed (m/s)	Wind Direction	#	Wind Speed (m/s)	Wind Direction	#
0	NO WIND	Case 1	0	NO WIND	Case 12
5	SIDE	Case 2	5	SIDE	Case 13
	BACK	Case 3		BACK	Case 14
10	SIDE	Case 4	10	SIDE	Case 15
	BACK	Case 5		BACK	Case 16
15	SIDE	Case 6	15	SIDE	Case 17
	BACK	Case 7		BACK	Case 18
20	SIDE	Case 8	20	SIDE	Case 19
	BACK	Case 9		BACK	Case 20
25	SIDE	Case 10	25	SIDE	Case 21
	BACK	Case 11		BACK	Case 22

The fire source was modelled as a burner with dimensions 1 m x 1 m (1 m²) placed in the center of the room with a prescribed constant HRR of 4 MW. All the simulations were run until 900 s and reached steady state before 600s. All the results presented for the parametric study are time averaged between 600 s and 900 s to compensate the oscillatory results caused by the LES turbulence model.

The gas temperature inside the compartment was measured by four thermocouple trees, one near each corner (distanced 0.25 m from the walls), being each tree composed by 10 thermocouples, at heights 0.6, 0.9, 1.2, 1.5, 1.8, 1.95, 2.1, 2.2, 2.3 and 2.35 m from the floor. The wall temperature and heat fluxes were measured in both internal and external wall surfaces in the back (windward wall for the back wind cases) and left (windward wall for the side wind cases) walls in three point in the middle width of the wall at heights 0.4, 1.2 and 2.0 m from the floor. The room geometry and measurement points are represented in Figure 1(a).

The atmospheric wind was modeled in FDS as an Atmospheric Boundary Layer through the Monin-Obukhov similarity theory, assuming an aerodynamic roughness length (z0) of 1.0, which corresponds to a landscape characteristic of suburbs, villages and forests, and neutral thermal stability. The reference wind speeds are implemented at a reference height of 10 m above the ground; this is the standard height where the wind parameters are measured in meteorological stations. The wind speeds applied in this study are in accordance with wind historical date, both from Brazil (Porto Alegre) and South Africa (Cape Town).

2.2 Mesh resolution

A mesh resolution analysis was performed to ensure the quality of the numerical results. It is a common knowledge that in LES codes, the quality of the results is directly tied to grid resolution. Although a complete mesh independency cannot be achieved, several criteria can be applied to determine an adequate mesh resolution.

According to McGrattan *et al.* (2020b and 2020c), for simulations involving fire plumes, the non-dimensional parameter D^*/δ_x gives a good estimate of how well the flow field is resolved. The greater this non-dimensional parameter, the more the fire dynamics are resolved directly (not being modeled by de sub-grid turbulence model), and the more accurate is the simulation. D^* is the characteristic fire diameter given by Equation (1) and δ_x is the nominal size of a mesh cell.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty T_\infty c_p \sqrt{g}}\right)^{2/5} \tag{1}$$

where $\dot{Q}$ is the heat release rate in kW, ρ_∞ is the ambient air density in kg/m^3, T_∞ is the ambient air temperature in K, c_p is the ambient air specific heat in kJ/(kg.K) and g is the acceleration of gravity in m/s^2.

As a rule of thumb, McDermott *et al.* (2010) suggested that values of D^*/δ_x of the order of 10 have historically been related to adequate grid resolutions, while the validation study sponsored by the U.S. Nuclear Regulatory Commission Salley e Kassawara, 2007, suggested D^*/δ_x values ranging from 4 to 16. Although this rule of thumb is largely applied and accepted by the fire safety community to determine the minimum suitable mesh resolution for modeling fire plumes, mesh sensitivity analysis are always recommended. For the current study, Table 2 presents the values of D^* and D^*/δ_x for the three uniform meshes sizes (δ_x =12 cm, δ_x =10 cm and δ_x = 6 cm) tested in the compartment region (mesh 4 in figure 2), both, for the validation case which is described in section 2.3 and the parametric study cases described previously.

Table 2. Non-dimensional mesh resolution parameters

HRR (kW)	D* (m)	D^*/δ_x		
		12 cm	**10 cm**	6 cm
2069 (validation case – ISOHept4)	1.29	10.73	**12.87**	21.45
4000 (parametric study cases)	1.67	13.95	**16.74**	27.90

As can be seen, all tested meshes were adequate according to this criterion. Additionally, a mesh sensitivity analysis was performed. The hot gas temperature results compared for the 3 different meshes applied to the validation case (ISOHept4) described by Lock *et al.* (2008) are shown in Fig. 1(b). As can be observed, meshes δx= 10 cm and δx= 6 cm presented very similar results, agreeing well with the experimental data. So, as a matter of computational time, once the δx= 10 cm mesh run in only 13.5% of the time required for running the δx= 6 cm mesh, the δx= 10 cm mesh was selected to be used for the compartment region (mesh 4 in Figure 2), both in the validation step and sensitivity study.

The measure of turbulence resolution (MTR) was also employed to confirm that the selected mesh was adequate to be applied in the parametric study when the atmospheric wind field was implemented. It is a posteriori analysis that gives a measure of how well the turbulence is being resolved in the domain in LES simulations. The MTR is a scalar quantity defined locally and was calculated for 14 points of interest scattered inside the compartment.

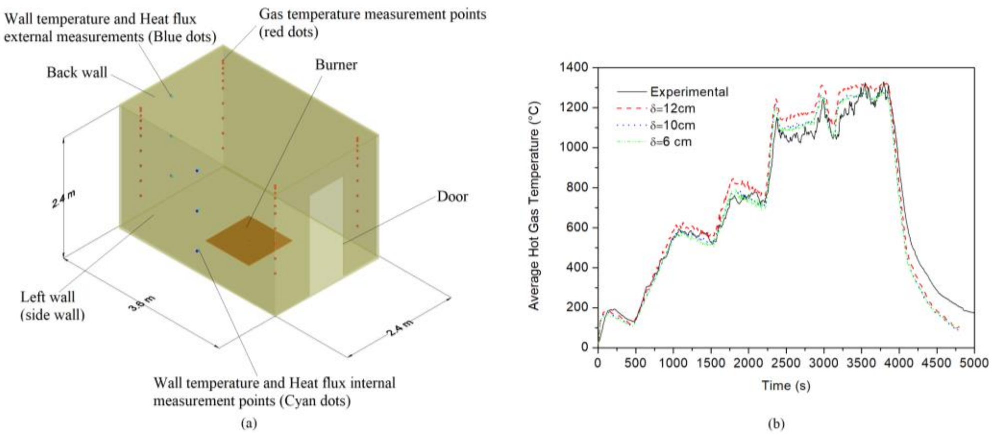

Figure 1. (a) Room geometry and measurement points; (b) Mesh sensitivity results for validation case ISOHept4

Pope (2004) stated that the MTR value must be less or equal to 0.2, which corresponds to the resolution of 80% of the turbulent kinetic energy in the flow field. Additionally, McDermott *et al.* (2010), suggested that MTR mean value near 0.2 provide satisfactory results for mean velocities and species concentrations in non-reacting, buoyant plumes. So, as the mean MTR value calculated for the case 17 (thermally-thin walls and 15 m/s side wind) with mesh 10 cm is equal to 0.13, which is less than 0.2, the selected mesh (10 cm) is adequate and capable to resolve more than 80% of the kinetic energy in the flow field on the compartment region.

In order to the wind field to develop adequately within the domain, it is recommended that obstructions should be kept reasonably far from the domain boundaries (McGrattan *et al.* 2020c). For this reason, it is recommended that the top, upstream, and lateral boundaries should be extended outwards 5 times the characteristic height of the buildings, and the downstream boundary extend 15 times this height. As in this study the compartment is 2.4 m height, the domain was extended outwards at least 12 m in the top, upstream, and lateral boundaries and 36 m at the downstream boundary. With those extensions the domain becomes very large, and using the same refined mesh required by the compartment region became too restrictive. So, coarser meshes were applied to the extended regions. The domain was divided into 10 meshes within 2 levels (5 meshes in each level), the domain dimensions and mesh refinements can be seen in Figure 2. Total number of control volumes in the domain for back wind cases is 606312 and for the side wind cases is 574182.

The MTR was also employed to ensure that the mesh refinement in the extended regions was enough to represent properly the flow field. The MTR was calculated in 10 points, 2 at the upstream of the compartment, 2 at each laterals and 4 at the downstream, the mean MTR for case 17 is equal to 0.08 and ensure that a proper mesh resolution is being applied to the domain extensions.

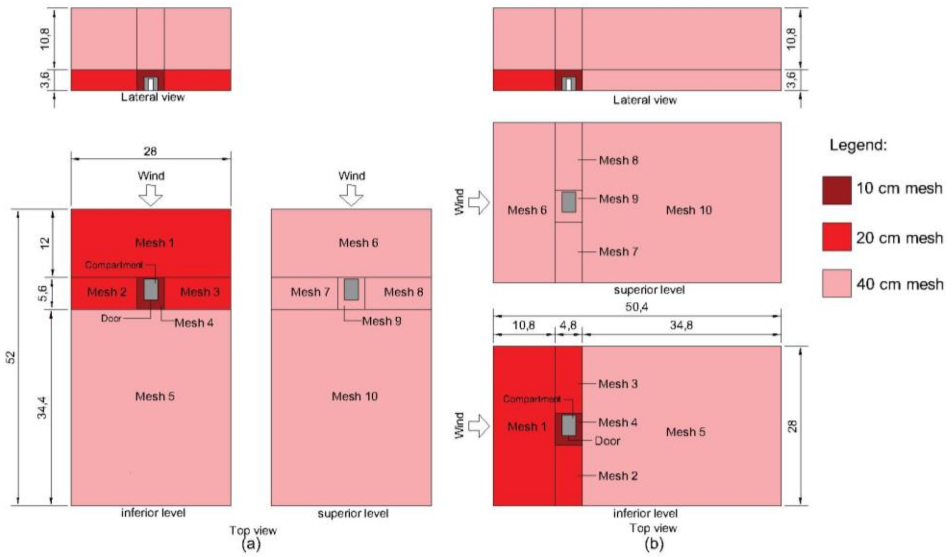

Figure 2. Domain and mesh refinement (a) Back wind cases (b) Side wind cases (all dimensions in meters)

2.3 Numerical model validation

Lock *et al.* (2008) conducted a series of full-scale under-ventilated compartment fire experiments, which included measurements of temperature, heat flux, species composition, heat release rate and mass burning rate.

To validate the numerical model, the under-ventilated experiment ISOHept4 conducted by Lock *et al.* (2008) was employed. It consists in a full-scale ISO 9705 standard room (2.4 m (L) × 3.6 m (W) × 2.4 m (H)) with a doorway of 0.8 m (W) x 2 m (H) in the middle of the short wall. The floor of the enclosure was raised 0.35 m above the concrete ground. The room was built using gypsum boards internally lined with one layer of 2.5 cm thick ceramic fiber blanket (K-liteTM HTZ). A free-burner with internal dimensions sized 1 m x 1 m (1 m²) and 0.1 m high, constructed from welded sheet steel 6.35 mm thick was placed in the center of the room. The mean peak HRR measured in this experiment was of 2069 kW. The materials thermal properties used in the FDS modeling are presented in Table 3. More information about the experimental set up can be found in Lock *et al.* (2008).

Table 3. Material thermal properties for validation case ISOHept4

Material	Thermal Condutivity [W/(m.K)]	Specific Heat [kJ/(kg.K)]	Density [kg/m³]
Gypsum board (Quintiere, 2017)	0.17	1.1	950
Concrete (Drysdale, 2011)	1	0.88	2100
Steel (Drysdale, 2011)	45.8	0.46	7850
Ceramic Fiber Blanket (K-LiteTM HTZ)	0.06 - 0.14[a]	1.13[b]	128[c]

[a] From INSWOOL-HTZ data safety sheet, [b]From K-lite HTZ technical data sheet and [c] From Lock *et al.*, [2008]

Figure 3 presents a comparison of the experimental and numerical results. As can be seen, the numerical model is capable to represent very well the under-ventilated compartment fire, so the numerical model is considered validated.

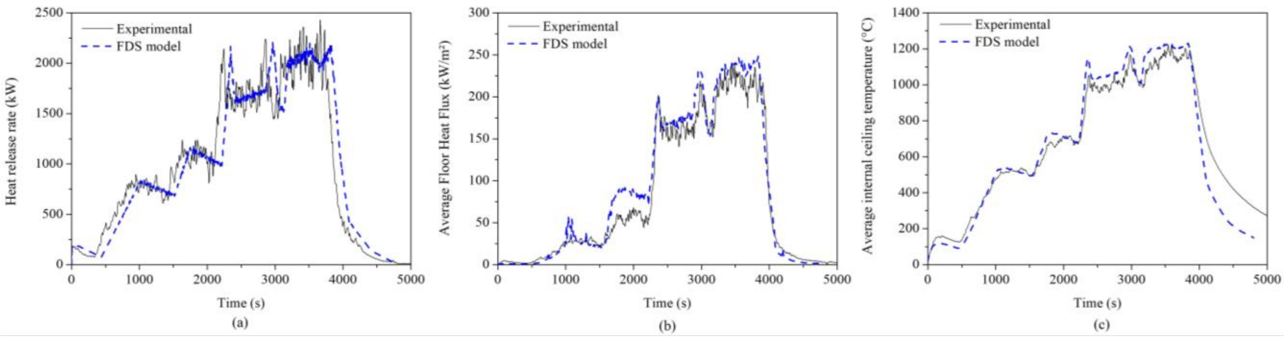

Figure 3. Validation results (a) heat release rate, (b) average floor heat flux and (c) average interior ceiling temperature

3. RESULTS AND DISCUSSIONS

3.1 Wind effect on Windward wall temperatures and hot gas temperature

Figure 4 presents the average windward wall (a) internal and (b) external temperatures, these results are an average of three measurements points in the wall. As can be seen in Figure 4(a), the windward wall internal surfaces presented an important reduction on the average internal surface temperatures when the wind speeds increased, with the exception of the thermally-thick walled compartment with the wind blowing in the back wall that presented just a slight reduction on the internal surface temperature. It can be observed that compartments with thermally-thick walls present higher internal wall surface temperatures than those with thermally-thin walls, this happens due to the higher thermal resistance of their walls, so less heat is transferred by conduction through the wall to the external surface of the wall and consequently the external surface would present much lower temperatures than the internal surface, as can be seen in Figure 4(b).

On the contrary, the thermally-thin walled compartments have a much lower conductive thermal resistance and for this reason, the temperature on both surfaces of the wall is almost the same, being practically constant through the wall thickness. For this reason, the thermally-thin compartments have higher external surface temperatures than the thermally-thick, and so, will conduct much more heat to the surroundings, both by radiation and convection. The external wall surface temperature also reduced when the wind speed was higher and thermally-thin compartments had their wall temperatures more significantly affected.

We can also observe that the back wall presented higher temperatures than the side wall (left wall) in all cases; this is probably due to the asymmetry caused by the presence of the door in the front wall. Air enters through the door and this tilts the fire and plume toward the back wall, heating it more than the side wall.

Figure 4(c) shows the average hot gas temperature inside the compartment, these results are an average of all measurement points of all 4 thermocouple trees. The thermally-thin compartment gas temperatures are lower than those from the thermally-thick compartment. This is expected once more heat is being conducted through the walls to the exterior. Also, we can observe that the gas temperature reduces with the increase in wind speed for all studied scenarios, although, again the scenario with thermally-thick walls and back wind was less affected than the others. This behavior is similar to the observed in the windward wall internal temperature.

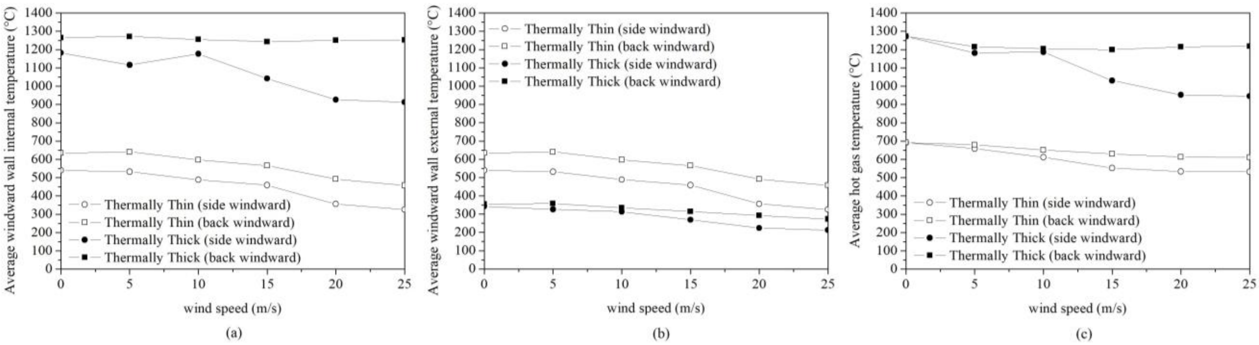

Figure 4. (a) Average windward wall internal temperature (b) Average windward wall external temperature (c) average hot gas temperature

Figure 5 shows the gas temperature profiles for all studied scenarios, these results are obtained from the average between the temperatures measured for the 4 corners in each height. Figure 5(a) shows the hot gas temperature profiles measured for the scenario where the compartment walls are thermally-thin and the wind is blowing in the side wall. We can see that increasing the wind speed the gas temperature reduces considerably, showing a reduction of about 23% from the case with no wind to the case with 25 m/s. The profiles are quite uniform, showing that the compartment is filled with hot gases and that a well-stirred condition happens. Similar results can be seen in Figure 5(b) for the scenario where the compartment boundaries are thermally-thin and the wind blows on the back wall, however in this scenario the gas temperature is less influenced by the wind speed (11.7%) than the case where the wind blows on the side wall. This may be for two reasons, the back wall is a little smaller than the side wall, and so the wind extracts less heat from it, or due the pressure gradients generated by the wind near the door that change the in and out flows through the door; more investigation is needed to confirm the cause.

Figure 5(c) represents the scenario where the walls are thermally-thick with side wind, while Figure 5(d) represents the scenario with thermally-thick walls with back wind. Again, we can see that the gas temperature was more affected by the wind speed when the wind was blowing on the side wall, showing a reduction of about 25.7% for this scenario and a reduction of about only 4.2% for the back wind scenario. In the thermally-thick cases the temperature profiles were less uniform, suggesting that the compartment gases were less stirred in these scenarios. In Figure 5(c) we can see clearly that the increase in wind speed decreases the gas temperature, however, especially in the cases with wind speeds of 5 and 10 m/s, we can observe that the temperatures measure in the lower part of the compartment are colder than those measured in the upper part, although they are still high temperatures. This is probably related to the mixing effect caused by the flow through the door. Through Figure 5(d), we can see that for thermally-thick compartments with the wind blowing on the back wall, the temperature decreases a little in the upper part of the compartment until the wind speed of 10 m/s, and then become practically constant, however again in the cases with wind speed of 5, 10 and 15 m/s the temperature profile was less uniform with lower temperatures in the lower part of the compartment than in the upper part. For this reason, the lower temperatures increased with the wind increase and the average temperature, showed in Figure 4(c), was practically constant with a slight decrease until 15 m/s and then a slight increase after that.

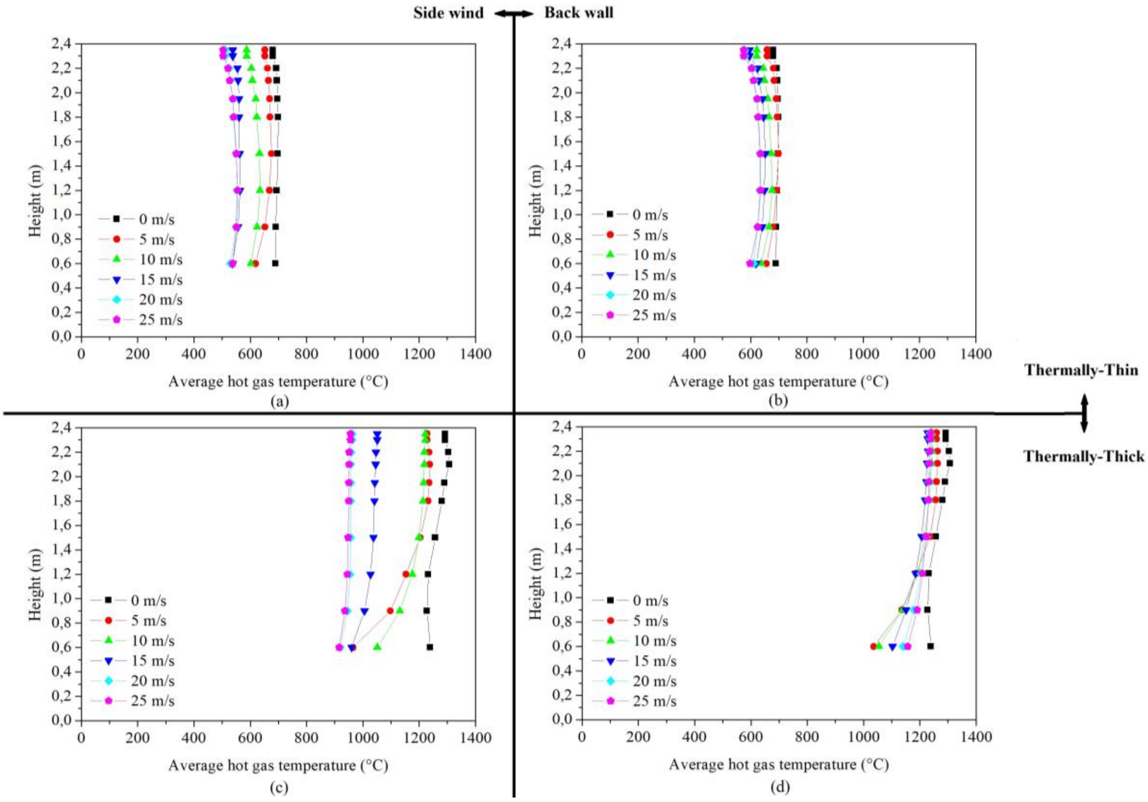

Figure 5. Gas temperature profiles for (a) Thermally-thin compartment with side wind (b) Thermally-thin compartment with back wind (c) Thermally-thick compartment with side wind (d) Thermally-thick compartment with back wind

3.2 Heat transfer through windwardwall

Figures 6 (a) and (b) present the average convective heat flux in the internal and external surfaces of the windward wall, respectively, and Figures 6 (c) and (d) show the radiative heat flux in the internal and external surfaces of the windward wall, respectively. These results are averaged between the three measurement points in the windward wall. From Figure 6(a), we can observe that the average convective heat flux in the internal surface of the windward wall happens differently for the thermally-thin and thermally-thick walls. The thermally thin walls presented convective heat fluxes from the fire environment to the wall (positive heat fluxes), while the thermally-thin walls presented mainly convective heat fluxes from the walls to the fire environment (negative heat fluxes). Also, when the wind speed was increased, the heat transfer to the walls in the thermally-thin increased, while the heat transfer from the walls in the thermally-thick decreased.

The external convective heat flux happens always from the walls to the surroundings (negative). It can be seen in Figure 6(b) that it increases with the wind speed for all scenarios, which happens once the presence of wind changes the convective heat transfer mechanism from natural convection to forced convection and the convective heat transfer coefficient increases with wind speed. The external convective heat flux is higher for the thermally-thin compartments, once they present higher windward external temperatures, also, we can observe that the scenarios with the wind blowing in the back wall seem to be more influenced by the wind speed and present higher external convective heat fluxes than those with side wind. These higher convective heat fluxes values in the external side of the wall when the back wall is the windward wall is probably related to the fact that the back wall tends to be hotter that the side walls.

The average radiative heat flux in the windward wall internal surface presented in Figure 6(c) happens always from the fire environment to the walls (positive), this is different from what was observed in the convective heat flux that may occur in both directions depending on the fire scenario. The convective heat flux depends on the local temperature difference between wall and hot gases, and depending on the fire scenario and the compartment height, the gases may be hotter or colder that the wall, on the other hand, part of the radiative heat flux come from the flames that are always hotter that the walls, so, the net radiative heat flux will be always transferred from the fire environment to the wall. We can also observe that the radiative heat fluxes are much higher than the convective heat fluxes, it was expected, once it is well known that due to the high temperatures of flames, radiative heat transfer is very often the dominating mechanism for transferring heat in a compartment fire. As can be seen in Figure 6(c), the radiative heat flux to the internal windward wall surface was much higher in the thermally-thin compartments, this happens due to the lower wall internal temperatures observed in these cases. An important decrease in the internal radiative heat flux was observed for the thermally-thin cases with the increase of the wind speed. The thermally-thick compartments presented lower internal radiative heat fluxes and were just slightly affected by the wind speed and direction. As the external convective heat flux, the external radiative heat flux also occurs always from the walls external surface to the surroundings (negative). Due to the increase in wind speed the external convective heat flux increases, what reduces the external wall temperature and consequently reduces the radiative heat flux to the surroundings. For higher wind speeds the radiative heat flux is equivalent or lower than the external convective heat flux, indicating a change in the main heat flux mechanism. The thermally-thin scenarios presented higher radiative heat flux than the thermally-thick, this is due the higher windward wall external temperature. All scenarios were affected by the increase in wind speed that decreased the radiative heat transfer, although, having a more important influence in the thermally-thin cases.

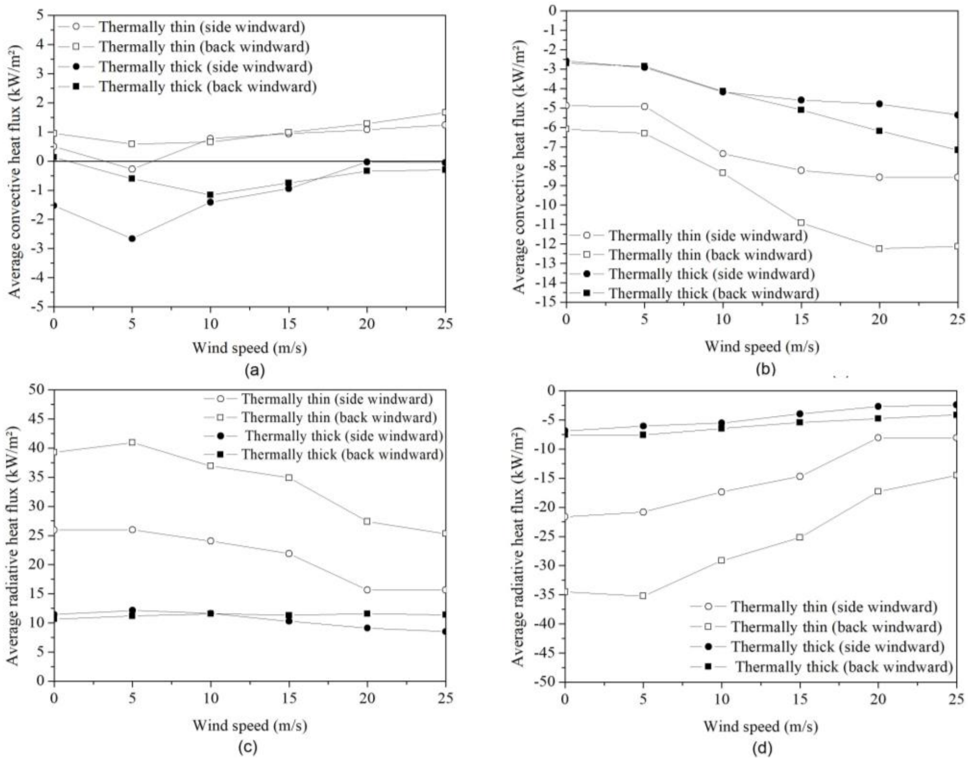

Figure 6. (a) Average convective heat flux on the internal windward wall surface (b) Average convective heat flux on the external windward wall surface (c) Average radiative heat flux on the internal windward wall surface (d) Average radiative heat flux on the external windward wall surface

The convective heat flux profiles, based in the measurements in three different heights of the windward wall are presented in Figure 7. Each Figure present the convective heat flux profile for both, the internal and external surfaces of the windward wall, the continuous lines representing the internal surface and the dashed lines the external surface. As can be seen in Figures 7 (a) and (b), the internal convective heat flux for the thermally-thin cases is always positive (from the fire environment to the walls) in the upper and middle parts of the wall, however, in the lower part of the wall for low wind spends, the convective heat flux is negative, this happens because locally the gas temperature is smaller than the wall temperature. The lower part of the compartment usually have the lowest gas temperatures, once the cold air inflow through the door happens near the floor, for this reason, the gas temperature near the floor may be lower than the wall temperature and the heat leave the wall in this region.

For the thermally-thick cases (Figure 7 (c) and (d)), we can see that in the upper part of the wall the wind do not affect significantly the convective heat flux, which is very low (around zero), sometimes positive and others negative, but in the lower part of the wall the convective heat flux is much more affected by the wind speed, presenting negative values (heat transfer from the walls). The cases with the wind blowing in the side wall presented a higher influence of the wind in the convective heat flux in the lower part of the wall.

For the external surface, it is possible to see that for all scenarios the convective heat flux is increasing with wind speed, and that the larger convective heat fluxes in the presence of wind happened at the center of the wall.

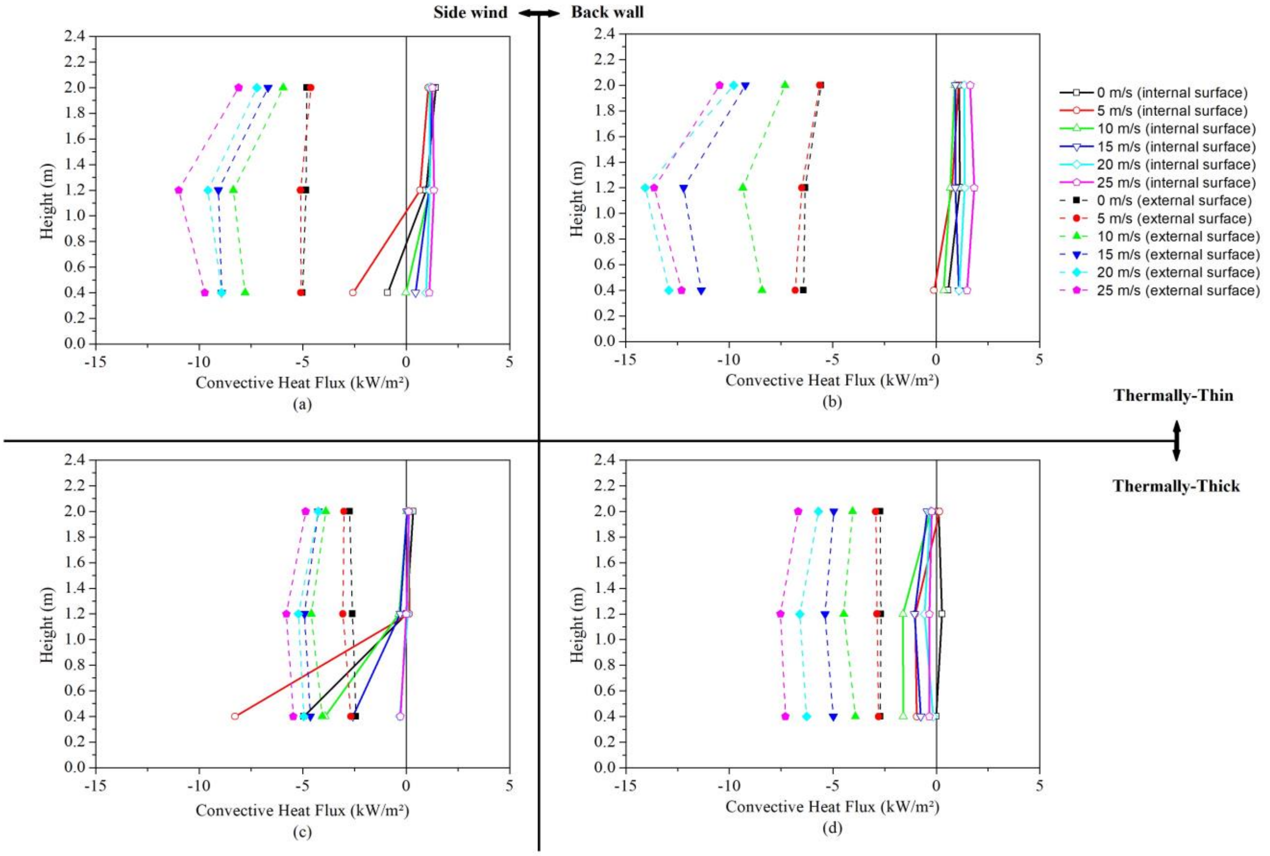

Figure 7. Convective heat flux profiles for (a) Thermally-thin compartment with side wind (b) Thermally-thin compartment with back wind (c) Thermally-thick compartment with side wind (d) Thermally-thick compartment with back wind

The radiative heat flux profiles, based in the measurements in three different heights of the windward wall are presented in Figure 8. Each Figure presents the radiative heat flux profile for both, the internal and external surfaces of the windward wall, the continuous lines representing the internal surface and the dashed lines the external surface. As can be seen from Figures 8 (a) and (b), the internal radiative heat flux for the thermally-thin is greatly affected by the wind speed and decreases with wind speed increase. For the scenario where the wind is blowing in the side wall (Figure 8(a)), the internal radiative heat flux is greatly affected in the upper part of the wall for all wind speeds decreasing with the increasing wind speed, however in the lower part of the wall, the radiative heat flux is higher and almost constant until the wind speed of 15m/s, than for higher wind speeds it reduces drastically, becoming almost the same that in the upper part. In the scenario where the back wind, although the radiative heat flux is higher in the lower part of the wall, it is being affected by the wind speed in all measurement points, and it also become more homogeneous for wind speeds above 15m/s.

From Figures 8 (c) and (d), we can conclude that the internal radiative heat flux to the walls was lower for the thermally-thick cases and it was much less affected by the wind speed. The scenario with side wind presented almost constant radiative heat fluxes at the upper and middle measurement points, however it presented higher radiative heat fluxes in the lower part for lower wind speeds, this radiative heat fluxes at the lower part of the wall reduced with the wind speed, becoming similar to the other parts of the wall for wind speed higher that 15m/s.

For the external surface, it is possible to see that for all scenarios the radiative heat flux decreased with wind speed, although thermally-thin compartments presented higher external radiative heat fluxes, which were more influenced by the wind speed and direction. The thermally-thick compartments showed a more homogeneous external radiative heat flux, while the thermally-thin cases presented larger radiative heat fluxes at the lower part of the compartment.

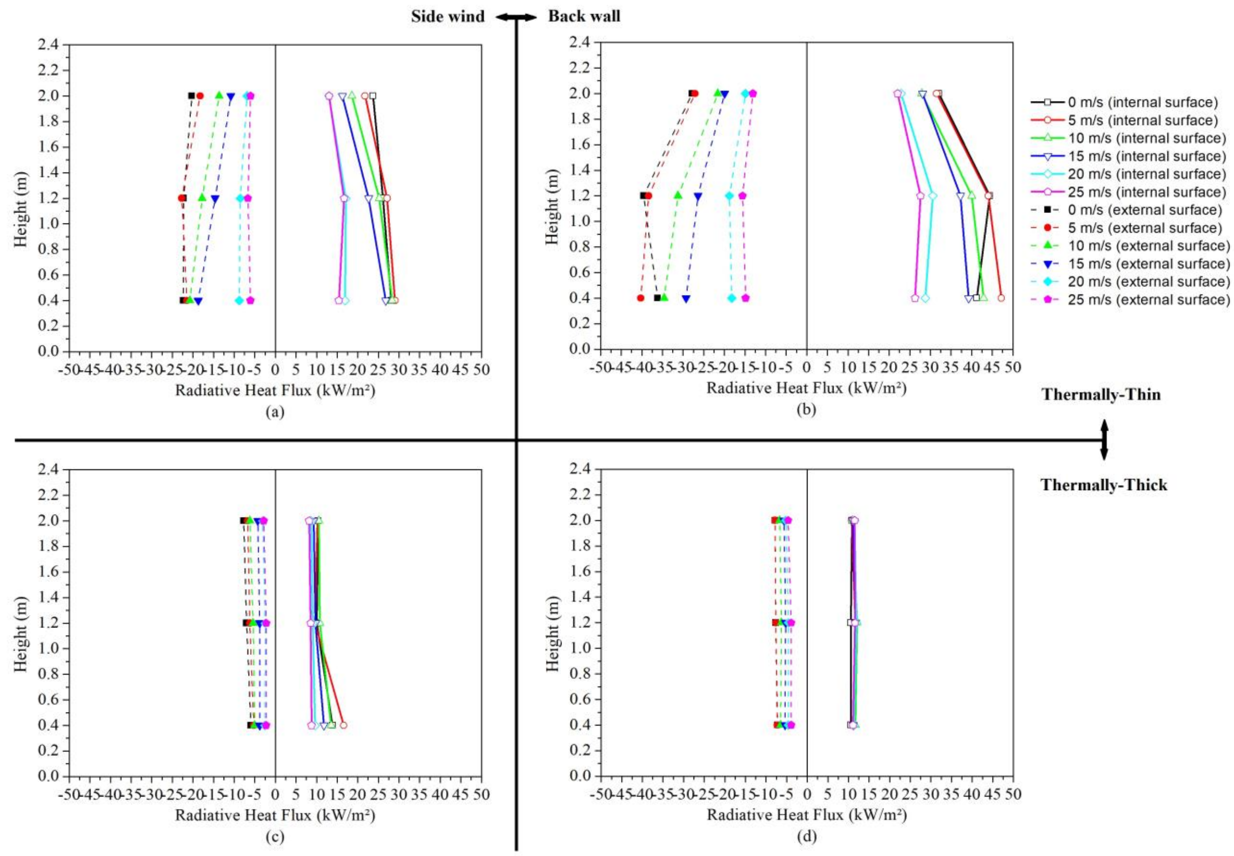

Figure 8. Radiative heat flux profiles for (a) Thermally-thin compartment with side wind (b) Thermally-thin compartment with back wind (c) Thermally-thick compartment with side wind (d) Thermally-thick compartment with back wind

4. CONCLUSIONS

This paper studied numerically the influence of the atmospheric wind on the fire dynamics and heat transfer in thermally-thin and thermally-thick under-ventilated post-flashover compartment fires using the software FDS. The validation step demonstrated that the FDS model is capable to reproduce adequately the full-scale under-ventilated compartment fire used in the parametric study.

The numerical experiments show that for constant heat release rates, the windward wall (internal and external) temperatures and the hot gas temperatures are inversely proportional to the wind speed. The thermally-thin scenarios presented lower windward internal surface and hot gas temperatures than the thermally-thick scenarios. Due to the thermal resistance of the thermally-thick bounded walls, their wall external surfaces are much colder than the internal and even colder than the thermally-thin bounded compartments. For this reason, the thermally-thin compartments conduct much more heat from the compartment interior to the surroundings through the walls.

The hot gas temperature was more influenced by the wind speed when the wind was blowing in the side wall, reductions of 23% and 25.7% were observed for the thermally-thin and thermally-thick compartments, respectively. Thermally-thin compartments presented more uniform gas temperature profiles, which indicate a well-stirred condition inside the compartment.

The average convective heat flux in the internal windward wall surface was different for the thermally-thin and thermally-thick compartments; the thermally-thin compartments presented mainly convection from the fire environment to the walls, while the thermally-thick presented the convective heat fluxes from the walls. The internal convective heat flux was less uniform for the wind blowing on the side, where the lower part of the compartment was more influenced by the wind speed. It was also possible to observe that in some cases the internal convective heat flux presented different directions for the upper and lower parts of the wall.

The external convective heat flux increased with the wind speed in all studied scenarios, while the external radiative heat flux decrease, both showed higher values for the thermally-thin compartments, which were more affected by the increase of the wind speed. The internal radiative heat flux also decreased with the increase in wind speed and the thermally-thin compartments were more affected.

It can be concluded that wind speed and direction can affect significantly the temperatures and heat fluxes through compartment walls, and that compartments with different wall thermal characteristics are affected differently.

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