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Fire Whirls in an Atrium: Experimental and Numerical Observations

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Introduction

High-rise buildings or complex architectural projects commonly contain atrium spaces, shafts, or large internal open spaces, where air currents can generate circulation and possible fire whirls. Swirling flames intensify heat release and cause spotting, accelerating spread mechanisms [1], which could entail substantial damage and even human casualties [2].

Research is mainly focused on small-scale pool, burner and gaseous fuel fire whirls [3], employing different facilities: rotating screens [4–7] and fixed-frames [8–15]. However, intrusive temperature and velocity measurements may modify the dynamics of the flame or the flow. In addition, non-intrusive methods' accuracy may depend, for example, on challenging optical properties [16].

Numerical models are widely used to understand whirls' behaviour better. They were first numerically reproduced with Fire Dynamics Simulator (FDS) in [17], followed by their modelling with other CFD software, such as Fluent in [18]. Spontaneous fire whirls were simulated in [19,20] and lately in [14]. In tall buildings, investigation and numerical models are focused on vertical shafts [21–23] by assessing the velocity fields and the shape and height of the flame.

This work evaluates pool fire whirls generated in an atrium with cross-ventilated conditions. The influence of the heat release rate (HRR) curves, experimentally measured or time-averaged, on the numerical models with FDS 6.7.5. is analysed.

Fire experiments

The fire experiments, described in Table 1, were performed in the Fire Atrium of Murcia, Spain [24–26].

Table 1. Fire experiments.

Test	Pan diameter [m]	Heptane [kg]	HRR* [MW]	T_{amb} [°C]	P_{amb} [Pa]
1	1.17	36	2.66	21.5	101,651
2	0.92	29	1.54	20.1	101,651

*Time-averaged

The Fire Atrium, with walls of thin steel, has the main volume of $19.5 \times 19.5 \times 19.5 \text{ m}^3$. It has a pyramidal-shaped roof (Fig. 1a) and inlet vents at the base, each with an opening area of $4.88 \times 2.5 \text{ m}^2$. The pool fires, located at the centre, consisted of two different pans filled with heptane over a base of water. The HRRs were measured with three load cells below the pan. Two of the four fans extracted a constant flow of $18.32 \text{ m}^3/\text{s}$.

A horizontal cable of 8 cm diameter at a height of 5.1 m was used to place some thermocouples (Fig. 1b).

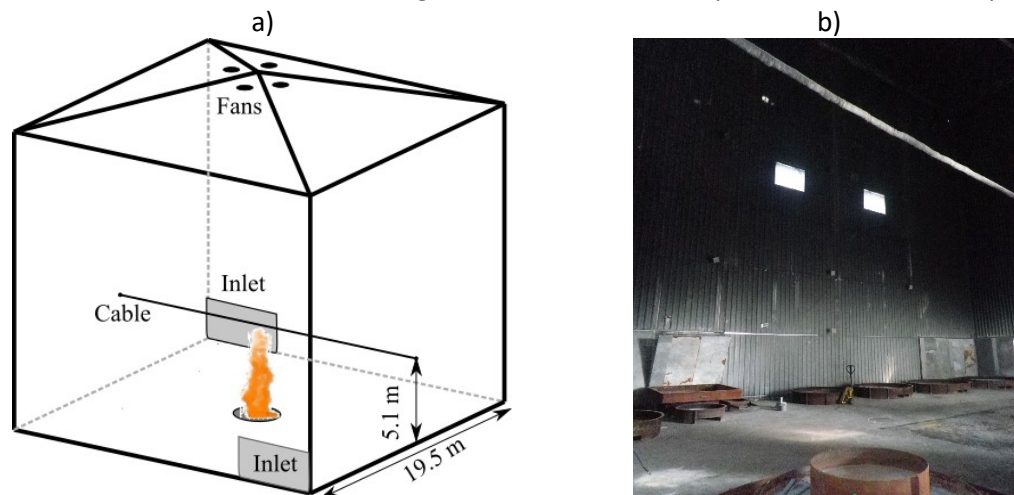


Fig. 1. a) Fire Atrium. b) Horizontal cable.

Numerical models

Fire Dynamic Simulator (6.7.5) [27] has been used to carry out the simulations. Extensions at the vents are necessary to simulate circular flow patterns accurately [28]. Three meshes are defined considering the highest HRR value of both tests, i.e. 2.66 MW for Test 1. The coarsest grid has a constant element size of 20 cm. Then, the medium grid has elements of 20 cm and a refined central region with elements of 10 cm (base area of 36 m^2). The finest grid contains two refined regions: a central region with elements of 5 cm (base area of 9 m^2) and a surrounding region up to 6 m from the centre, with a size of 10 cm.

As the whirls were observed to interact with the cable during the experiments, two numerical models of the atrium were defined: with and without the cable.

Fire whirls characterisation

Circulation highly characterises the behaviour of fire whirls. A radial inflow is produced by the imbalance of centrifugal force near the ground pressure gradient, increasing the heat input to the fuel and, consequently, its evaporation rate which enlarges the flame height [29]. This vortex consists of two regions: an inner core

with vorticity and an outer free vortex without it. The evolution between both regions is smooth for the Burgers vortex, which is considered the best description of the velocity field [4,16,34,35].

The radial temperature profile, for the continuous flame, is of hump-type, because of the inner fuel-rich core. The temperature decreases outside this core. Above, in the fire plume region, the maximum excess temperature ($\Delta T_m = T - T_{amb}$) approaches the centre as a Gaussian profile.

Results and Discussion

In this short version of the original paper [30], the results obtained for Test 1 are shown.

Experimental HRR

The measured and the time-averaged HRR curves are shown in Fig. 2. The time-averaged curve has been defined as: 0%, 62.4%, 89.1% and 100% of its time-averaged value for 0 s, 10.7 s, 81.5 s and from 200 s to the end of the test, respectively [31,32].

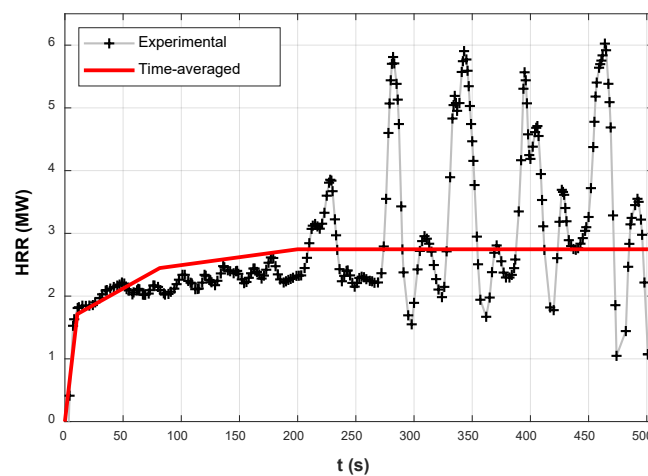


Fig. 2. Measured and time-averaged HRR curve.

Five fire whirls were generated, i.e. the sudden growth of the measured HRR (Fig. 3). They can be also seen in the videos of the online version of the original paper [30]. Before the formation of every whirl, the flame wandered around the centreline for an approximate averaged period of 60 s. As can be observed, the whirls reached the cable (Fig. 3.).

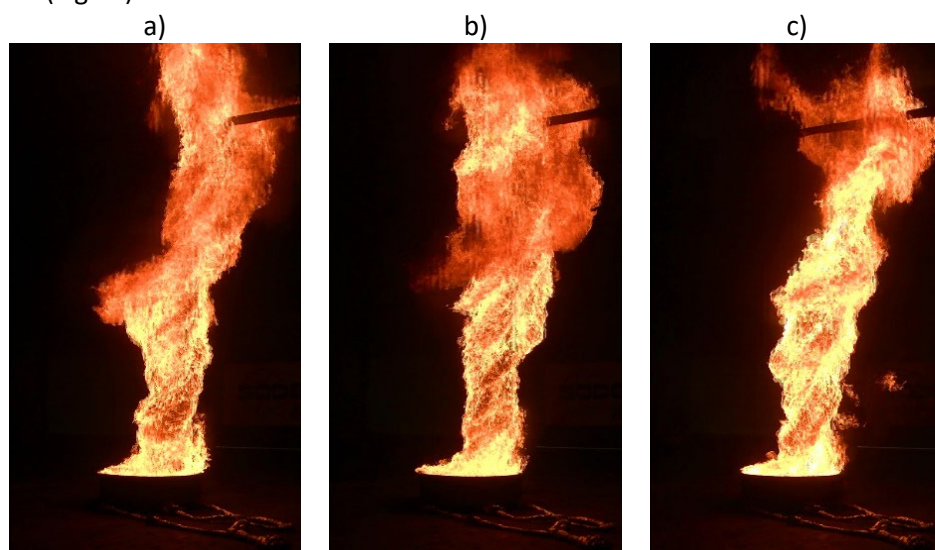


Fig. 3. Fire whirls interaction with the cable.

To verify that whirls are numerically captured, the tangential velocity (u_θ) and the excess temperature (ΔT), at successive heights (in meters), are represented in Fig. 4. The ratios of u_θ with respect to its maximum $u_{\theta m}$, as a function of r/r_o , where r_o is the maximum tangential velocity radial distance, are compared with the Burgers vortex (BV). The ratios of the ΔT and its maximum ΔT_m as a function of r/r_T , where r_T is the temperature core radius and $\Delta T = 0.5\Delta T_m$, are also shown.

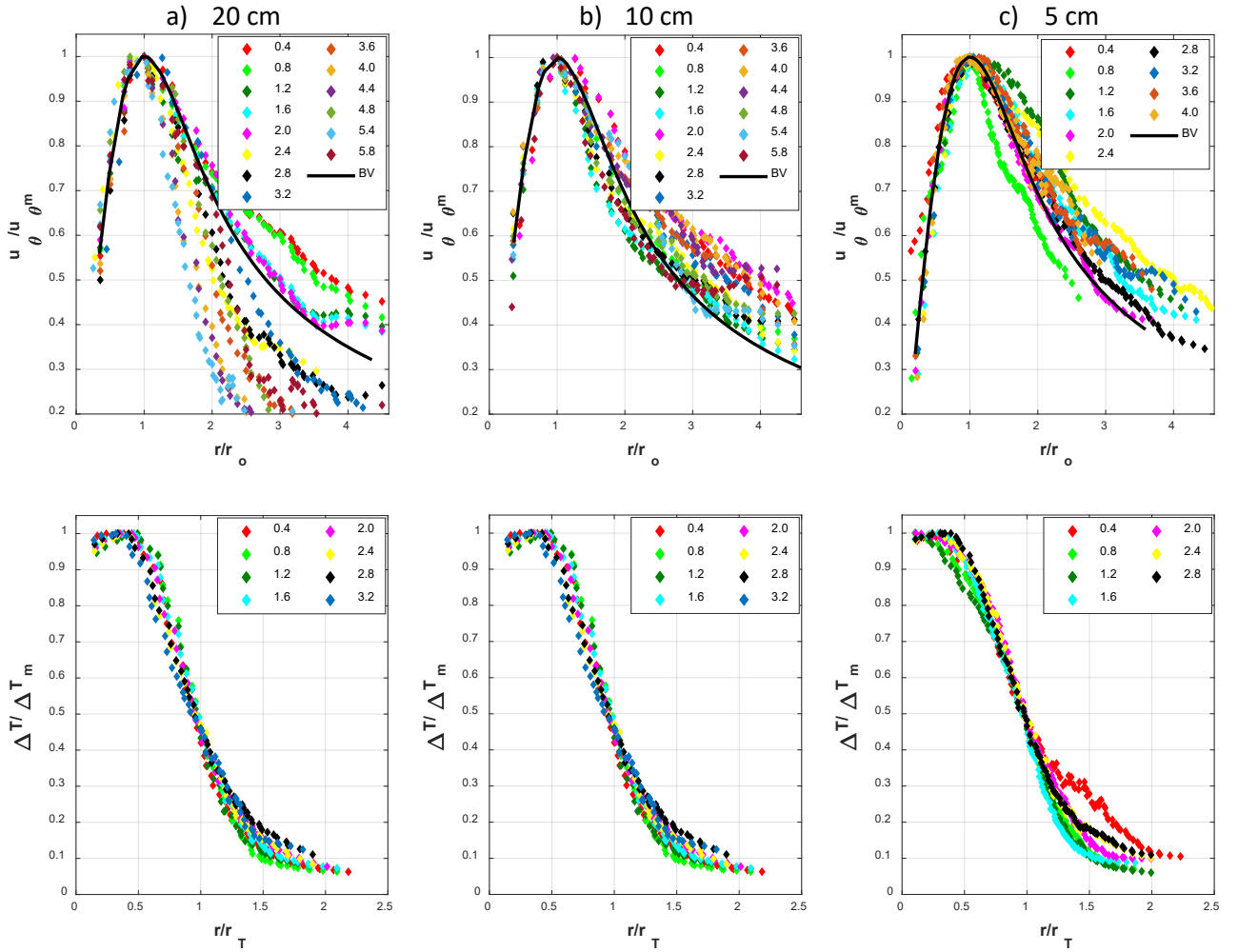


Fig. 4. Normalised tangential velocity and excess temperature at different heights.

With the three meshes, the Burgers vortex is well predicted. Only with the medium and finest grids, the excess temperature captures both the continuous flame and the plume regions. Here, the continuous flame region is only represented. The temperature core radii and the tangential velocity fields are also shown in Fig. 5. These

results confirm that the whirl is not well predicted with 20 cm because the values achieved are very low.

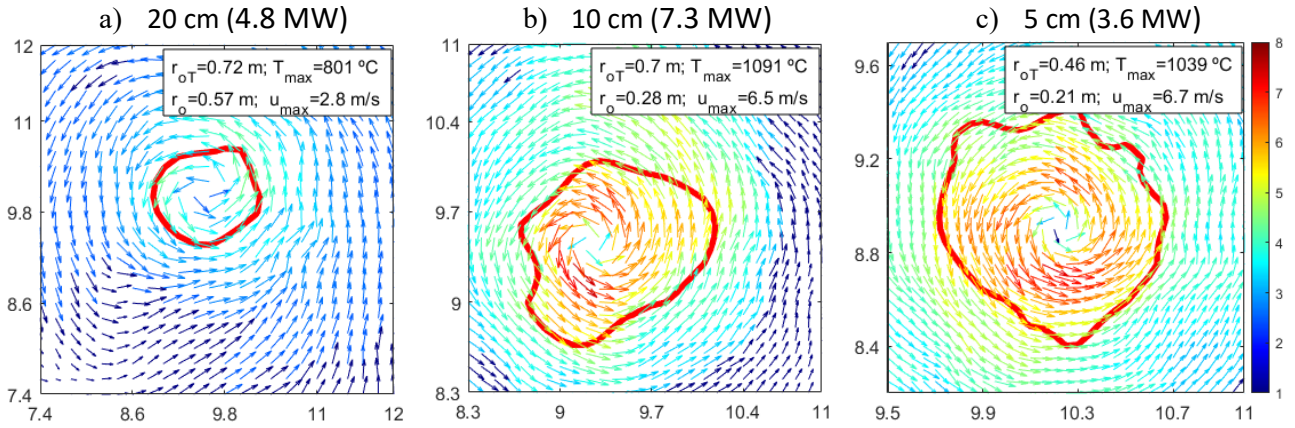


Fig. 5. Tangential flow field and temperature core radii.

The temperature far from the plume (30 cm from the walls, at two heights) is also assessed to understand how these whirls influence the production of smoke. The maximum temperatures achieved are shown in Table 2 (maximum relative error below 8.5%).

Table 2. Maximum temperatures near the walls of the atrium.

Height		Exp (°C)	Temperature (°C) / Error (%)		
			20 cm	10 cm	5 cm
7.5 m	Without cable	98.6	105.6 / 7.0	104.0 / 5.5	98.2 / 0.4
	With cable		104.0 / 5.5	93.9 / 4.8	92.7 / 6.0
15 m	Without cable	109.1	114.5 / 5.0	118.4 / 8.5	105.9 / 2.9
	With cable		116.3 / 6.6	110.1 / 0.9	99.9 / 8.4

The results indicate that these numerical models accurately predict the temperatures of the far field. The coarsest grid seems to behave well and fast, but fire whirls are only accurately predicted with the finer grids. Moreover, with the measured HRR as an input, the numerical whirls become more unstable. In addition, the computational cost is a significant issue when modelling these types of fire scenarios, and small obstacles may affect the results. When introducing the cable in the models, the number of whirls increase as observed in the experiments.

Time-averaged HRR

The temperatures of the different models in the near-field, i.e. fire plume at 4.6 m high, are shown in Fig. 6. This comparison is difficult to analyse due to the thermal inertia of the thermocouples and turbulence, although it allows to determine the evolution of the whirls formation. With the finest grid, the temperature is underpredicted because of the violent flame rotation; only a relevant fire whirl is generated although less stable than when not considering the cable, as was experimentally observed.

a) Without cable

b) With cable

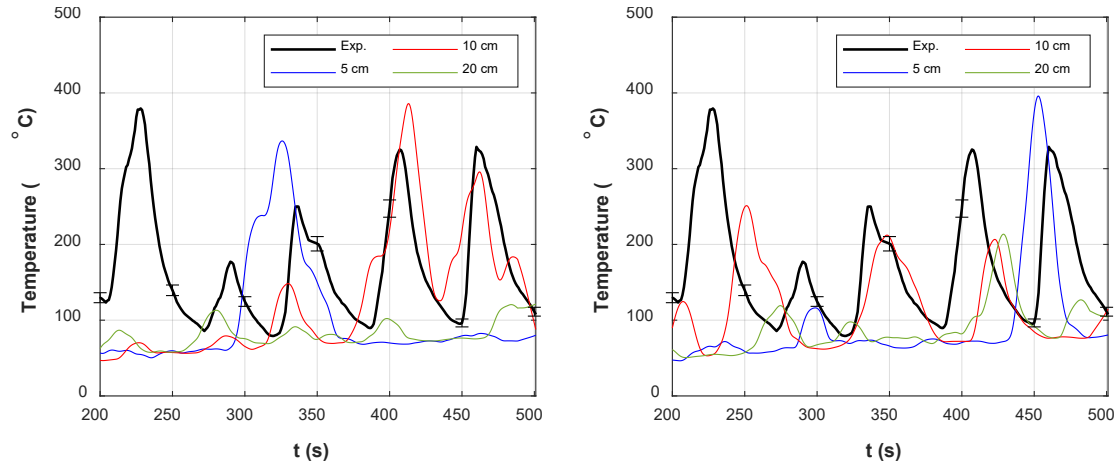


Fig. 6. Temperature in the fire plume at the height of 4.6 m.

The results obtained with 10 cm seem to be reasonably reliable, although the flame does not reach the cable because of the reduced time-averaged HRR value. This can be observed by u_θ in Fig. 7. A nearly constant circulation is achieved up to 2.4 m high. Then, the circulation decreases, as observed at the height of 3.2 m.

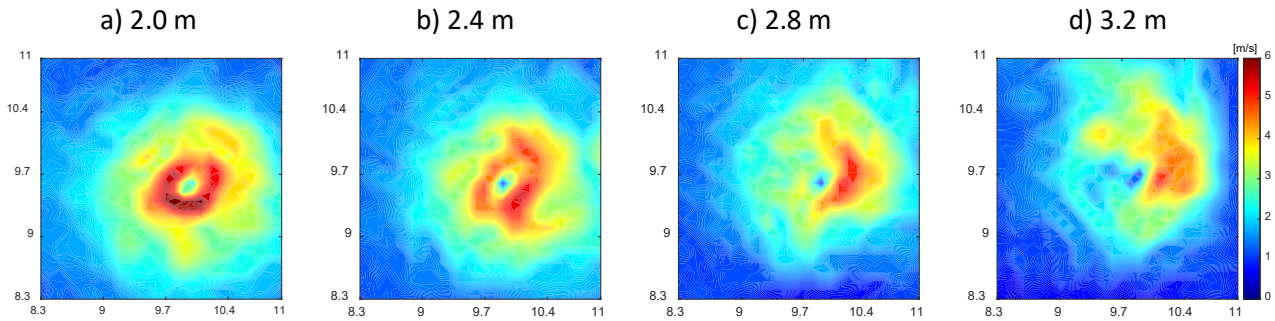


Fig. 7. Tangential velocity at different heights (421 s).

The numerical results in the far-field follow the growth of the experimental temperatures up to 350 s with differences lower than 5% (Fig. 8). Then, the predicted growing trend diminishes, underpredicting the measurements. The temperatures at the end of the test are show in Table 3, with maximum error of 17.7%.

a) Without cable

b) With cable

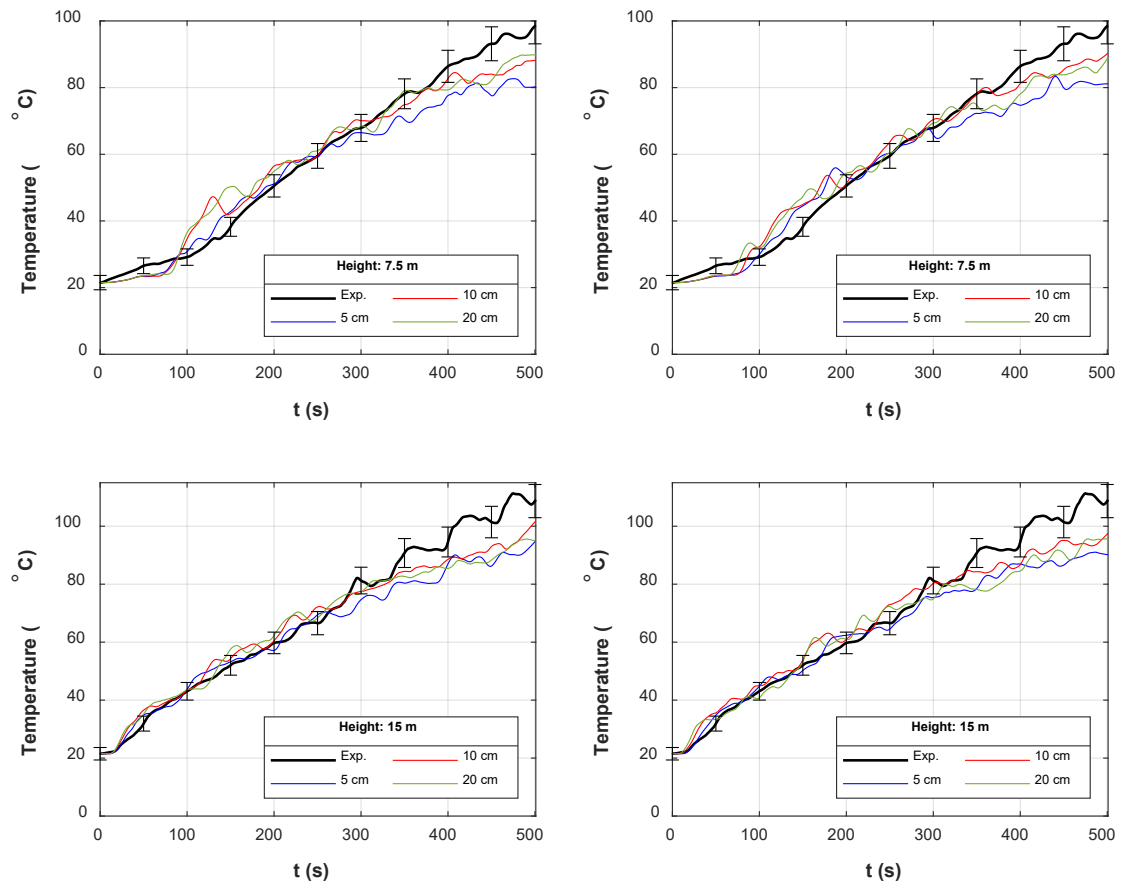


Fig. 8. Temperature near the walls at the height of 4.6 m.

Table 3. Maximum temperatures near the walls of the atrium.

		Temperature (°C) / Error (%)			
Height		Exp. (°C)	20 cm	10 cm	5 cm
7.5 m	Without cable	98.6	89.8 / 8.9	88.2 / 10.6	80.3 / 18.6
	With cable		89.0 / 9.7	90.3 / 8.4	81.1 / 17.7
15 m	Without cable	109.1	94.8 / 13.1	101.7 / 6.7	95.0 / 12.9
	With cable		95.7 / 12.3	97.5 / 10.6	90.2 / 17.3

Time-averaged HRRs allow the prediction of more stable whirls. However, fire whirls are weaker, which may reduce smoke production.

Conclusions

The main conclusions are herein summarized:

- Fire whirls are numerically captured with both HRR curves using FDS, although not generated in the expected time instants. The tangential velocity field follows the Burgers vortex, and only with the finer grids, continuous and plume regions are identified.
- The time-averaged HRR curve captures better the generation frequency of whirls. However, a higher discrepancy in the far-field temperatures is obtained.

- Small objects proximate to the flame, such as the cable, affects the results, which could influence fire spread mechanisms. Nonetheless, their modeling entails a significant increase in the computational resources of the models.

Swirling flames can be formed in spaces with venting characteristics included in current standards and regulations. They may accelerate spread mechanics, favoring unforeseen damage if these possible fire scenarios are not considered in fire safety designs.

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