NUMERICAL MODELING OF SCALED DOWN FIRE EXPERIMENTS

B.E. Mateusz Zimny

The Main School of Fire Service
Juliusza Slowackiego 52/54 st.
01-629, Warsaw
e-mail: mzimny94@gmail.com

ABSTRACT

The Froude-number based reduced-scale modeling is a technique commonly used to calculate the flow of heat and mass in building fires. The ratio of internal forces to the bouncy forces, plays a pivotal role within these equations. The root of the method is the thermodynamic model of a flow in a compartment and several non-dimensional flow numbers based on the proportionalities of the Navier-Stokes and heat transfer equations. The results for conducted experiments show, that the applicability of Froude-number reduced-scale modelling has its limitation related to the scale. We propose the method for the sensitivity analysis by CFD modeling. This paper is an attempt to define the range of the credible scale modeling with using Froude-number and the capability to perform a sensitivity analysis using CFD simulations.

Keywords: Froude-number, FDS, CFD, fire scale experiments

INTRODUCTION

There is continuous progress in the reflection of the fire phenomenon in computer models [1]. There is also growing number of the application of the computer software to the complex fire problems [2]. Computer models are continually gaining the accuracy and the scope of the modeled fire phenomena. However, due to limitations in representation of many fire related phenomena, computational costs and uncertainties related to numerical investigation, physical experimentation in reduced-scale modeling are still a popular tool.

There are two governing non-dimensional numbers in low-Mach – fire related flows, namely Reynolds (Re) and Froude (Fr) number. However, the Fr scaling conflicts with the Re preservation by two different results for velocity in the scale models. There are analyses [3], that prove that in fire related flows, one should preserve the Froude-number, not the Reynolds number, when scaling is applied. In this case, so-called partial scaling is adopted, that favors the Fr over the Re [4].

The Fr scaling assumes, that two fires are similar to each other, if the Froude-number characterizing both fires is equal, and there is geometrical and hydraulic similarity of the systems in which the fires take place. If the Fr is preserved, the temperatures measured in the reduced- and full-scale fires should be equal. An illustration of the Froude-number scale fire modelling concept is shown in Figure 1.

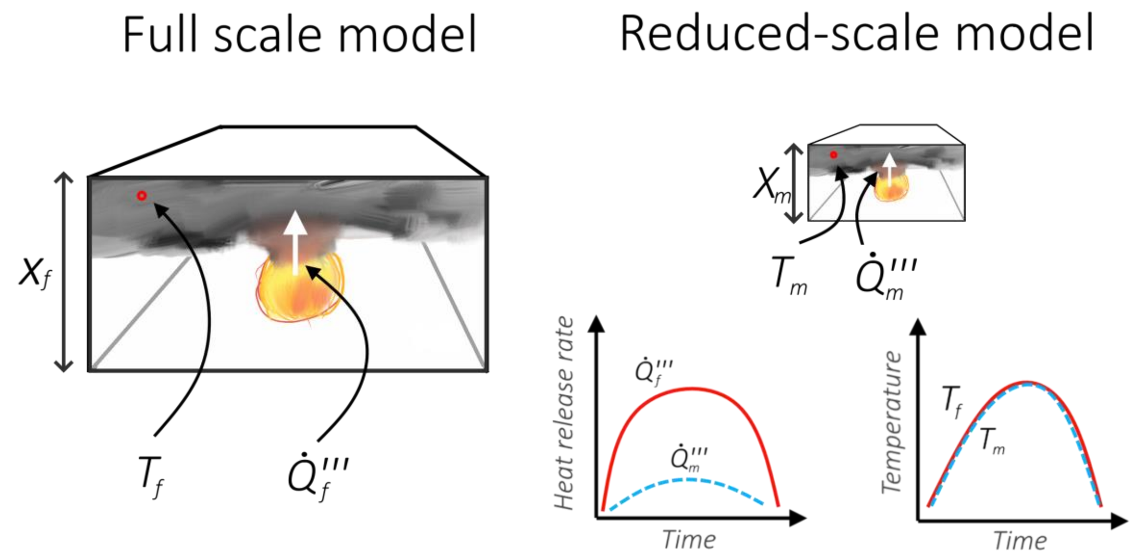


Figure 1. The idea of the Froude-number reduced-scale fire modelling. Illustrating the concept of scaling down the heat release rate of the fire to model a fire, that causes similar consequences in the scaled down (geometrical) compartment [5]

The approach of the Fr scaling must be used with care, despite its popularity. Spalding emphasized that partial scaling is "an art" and not a science, due to problems in properly relating the behavior of full-scale system to the one of the model [6]. Among these problems, the most common are with the scaling the chemistry of combustion and the flow turbulence [6]. Model-scale experiments are common tool in the research about tunnel fires and also can be used as a complement to large scale testing [7] because of high cost of full scale experiments and difficulties with their realization. An illustration of the implementation of model-scale in tunnel fire experiments is shown in Figure 2.

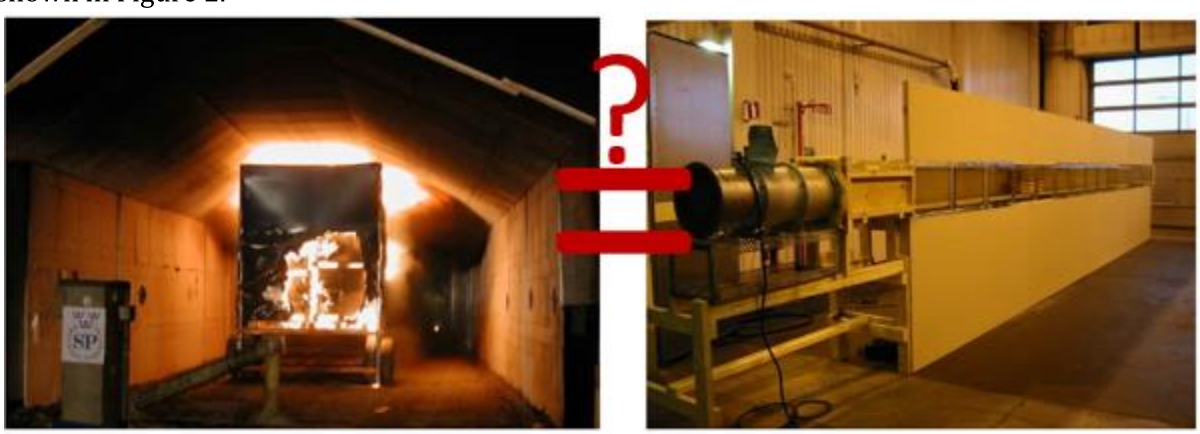


Figure 2. Two fire experiments in different scales representing the same fire. The left picture shows a photo from Runehamar tunnel fire tests [8]*. The right photo shows 1:23 model-scale representation of these tests* [7]

With model-scale experiments the two questions usually arises. The first question is about the representation of the all fire phenoms and whether can we really use this technic to all fires? The second most common question in this matter is which scale size is appropriate. An example of research performed in small scale, along the geometrical scale used is shown in Table 1.

Table 1. Examples of scale size used in fire research

Scale	Compartment of interest	Number of experiments	HRR (Reduced scale)	Source
1:1	Road tunnel	5	6000 -202,000 kW	[8]
1:2	Railway car	10	90 -1247 kW	[9]
1:2	Compartment	n/a	n/a	[10]
1:3,5	Single family house	2	up to 100,000 kW	[11]
1:4	Compartment	165	n/a	[12]
1:7	Room	3	300 -1500 kW	[13]
1:8	Cellar	1	18.31 kW	[14]
1:8	Corridor	5	50-300 kW	[15]
1:10	Shopping mall	48	7.6 kW	[16]
1:10	Shopping mall	25	6-10.3 kW	[17]
1:12	Road tunnel	5	15.1-72.8 kW	[18]
1:13	Road tunnel	61	7.81-215.1 kW	[19]
1:15	Road tunnel	28	6.7-430.1 kW	[20]
1:20	Road tunnel	54	n/a (5-25 MW in full scale)	[21]
1:20	Subway tunnel	116	1.48-3.52 kW	[22]
1:23	Road tunnel	12	102.2-320.8 kW	[7]
1:48	Train tunnel	1	0.31-1.88 kW	[23]

In modern fire modelling it is assumed, that two fires can be considered similar if the following requirements are met [5]:

- Froude-number of both of the fires is equal;
- All geometrical features related to the fire and the environment are scaled with the same scale;
- The fire is occurring at well-ventilated conditions, i.e. the combustion is not significantly influenced by the reduced-scale, and the combustion efficiency in full and reduced-scale is similar;
- The flow in the buoyant plume is turbulent.

If the Froude similarity criterion is met, and the Reynods criterion is satisfied, the other relevant parameters that describes the flow of mass and heat in the compartment will scale as summarized in reference [24] and listed in Table 2.

Table 2. Relations between the values in the full and model-scale

Parameter	Unit	Scale relations	Equation number
Heat Release Rate	[kW]	$\frac{\dot{Q}_m}{\dot{Q}_f} = \left(\frac{x_m}{x_f}\right)^{5/2}$	(1)
Velocity	[m/s]	$\frac{V_m}{V_f} = \left(\frac{x_m}{x_f}\right)^{1/2}$	(2)
Time	[s]	$\frac{t_m}{t_f} = \left(\frac{x_m}{x_f}\right)^{1/2}$	(3)
Energy	[kJ]	$\frac{E_m}{E_f} = \left(\frac{x_m}{x_f}\right)^{3}$	(4)
Mass	[kg]	$\frac{\dot{m}_m}{m_f} = \left(\frac{x_m}{x_f}\right)^{3}$	(5)
Temperature	[K]	$T_m = T_f$	(6)

METHODS AND MATERIALS

Experimental setup

The Froude-number based scaling technique was used in a series of full-scale (1:1) and small scale (1:4) physical experiments on the development of a hot smoke layer in a small size fire, in a small not ventilated compartment. As a fuel of fire the n-Heptane was used in all the experiments. In each experiment, the size of the fire was scaled through reducing the size of the pan with fuel.

The physical experiments in scale 1:1 were performed in the Building Research Institute smoke detector testing chamber (Figure 3-left). The dimensions of the chamber are 9.60 x 9.80 x 4.00 m. Two experiments, each consisting of three repeats were performed. In the first series a fuel tray with dimensions of 0.33 x 0.33 m^2 was used (further referred to as series A), and in the second series, a fuel tray with dimensions of 0.50 x 0.50 m^2 was used (series B). In both full-scale experiments, the fuel was 1 l of n-Heptane. The Heat Release Rate (HRR) was determined through mass loss rate measurements of the fuel tray, with the assumed Heat of Combustion value Hc = 44 400 kJ/kg. No ventilation was used in the experiment (the compartment was sealed).

The reduced-scale experiment was performed in a scaled down model of the test chamber (1:4)(Figure 3-right), with the dimensions of 2.40 x 2.45 x 1.00 m^3. All physical features of the compartment were scaled down accordingly, except the fuel tray. The size of the fuel tray was first determined through geometrical scaling and then refined based on mass-loss measurements of the combustion of n-Heptane so that the similarity of (5) and (9) is explicitly met. The correction to the size of the tray was within 10% of the geometrical size.

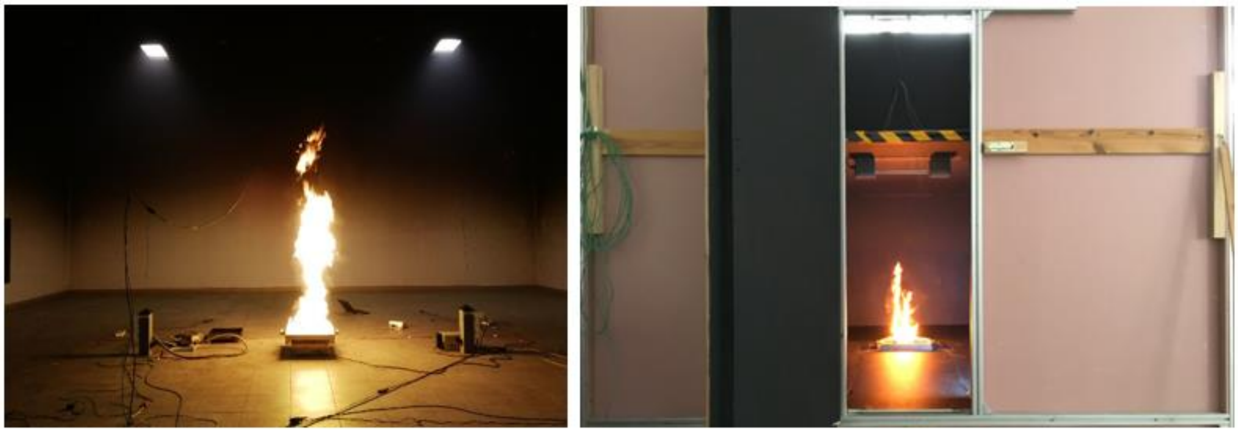


Figure 3. Full-scale (left) and small-scale (1:4)(right) experiments on the free burning of n-heptane [5]

The summary of the all assumptions for the experiment is given in Table 3. Each of the experiments was repeated three times, and the main conclusions are formed based on the averaged values obtained from the experiments.

Table 3. Overview of the experimental input parameters

Series	**Series A**		**Series B**	
	1:1	**1:4**	**1:1**	**1:4**
HRR [kW]	81.7 kW	2.55 kW	158 kW	4.94 kW
Volume of fuel [l]	1.015	0.0158 l	1.015 l	0.0158 l
Mass of fuel [g]	0.6943 kg	0.0108 kg	0.6943 kg	0.0108 kg
Duration of the fire (real time) [s]	350 s	175 s	181 s	90.5 s
Tray size [m]	0.33 x 0.33 m	0.075 x 0.075 m	0.50 x 0.50 m	0.125 x 0.125 m

Numerical setup

The fire experiments (scale 1:1 and 1:4) described in the last subsection were recreated with Fire Dynamics Simulator (FDS) code (version 6.7.0). FDS is a Computational Fluid Dynamics (CFD) code developed for modelling of low Mach number fluid flows, with an emphasis on smoke and heat transport as a result of fires [25].

In order to determine the scope of Fr scaling applicability to small fires and the validity of FDS, 3-D computer model of laboratory was prepared. An illustration of the model is in Figure 4. To prepare the CFD model geometry GUI software called PyroSim developed by Thunderhead Engineering [26] was used. The dimensions of the model (full scale) were 9.6 m x 9.6 m x 4.2 m.

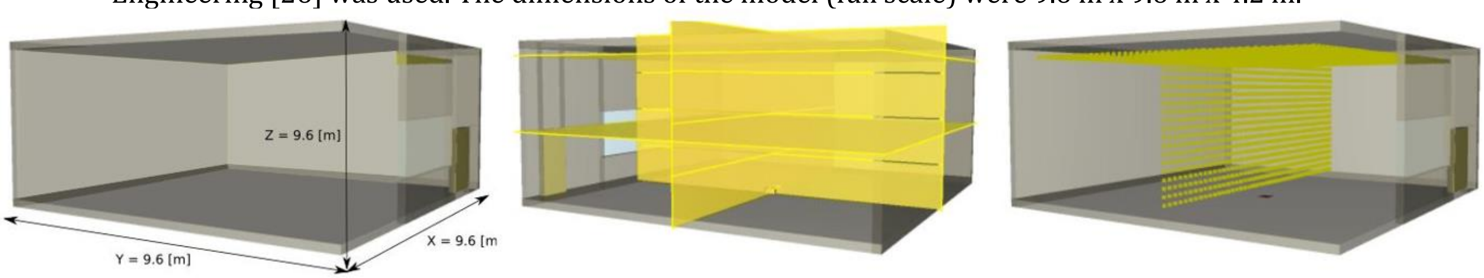


Figure 4. Full- 3-D model of the laboratory in full scale and the arrangement of 2D-slices and measuring devices used in the result analysis

The location of measurement points and planes in simulations are shown in Figure. 4. 2-D slices were used to illustrate the temperature. Moreover, a matrix of point measurement devices (PMD) has been prepared to measure the temperature distribution, forming an array in two planes: Y = 5.0 and Z = 4.0 with 0.2 m interval. In the reduced-scale simulations the location and interval has been scaled following the geometrical scale of the model.

A total number of 12 computer simulations were performed i.e. 6 simulations per series. Table 3 provides a summary of the information on numerical models. Reduction of the geometric dimensions of the model caused the compression of the computing domain and the size of individual cells. Therefore, in all different scenarios the amount of grid cells was constant and equal to 3 897 600. Thus, both the resolution and position of the measurement apparatus are constant in relation to the full-scale model. The comparison of the dimensions of all CFD models is shown on Figure 4.

Table 4. Parameters of the FDS numerical models

Scenario	Scale	Model dimensions [m]	Grid size [m]	Number of grid cells
1 A, B	1:1	9.6 x 9.6 x 4.2	0.05	3 897 600
2 A, B	1:2	4.8 x 4.8 x 2.1	0.025	3 897 600
3 A, B	1:4	2.4 x 2.4 x 1.05	0.0125	3 897 600
4 A, B	1:10	0.96 x 0.96 x 0.42	0.005	3 897 600
5 A, B	1:20	0.48 x 0.48 0.21	0.0025	3 897 600
6 A, B	1:50	0.192 x 0.192 x 0.084	0.001	3 897 600

Following the geometrical scale, the HRR of a test-fire was reduced (Equation (1)), as well as the simulation time (Equation (3)). Before starting the calculations, the time step of recording the results in individual simulation has been determined so that regardless of the length of calculations, 200 records are obtained. This allows to compare the results of numerical analyses in dimensionless time, regardless of the scale of analysis. However, for clarity, all results are shown in scaled-up time, as in the scale 1:1 (Equation (3)). Table 5 show scaled-down, tray size, HRR, calculation time and time step of records for each simulation.

Table 5. Overview of the CFD simulations input parameters

Scenario	Scale	Tray Size	HRR Per Unit of Area [kW/m²]	Caculation Time [s]	Lenght of a Time Step for Results Analysis [s]
1A	1:1	0.35 × 0.35	750	350	1.75
1B	1:1	0.5 × 0.5	584	197	0.975
2A	1:2	0.175 × 0.175	530	247	1.24
2B	1:2	0.25 × 0.25	414	139	0.7
3A	1:4	0.0875 × 0.0875	375	175	0.88
3B	1:4	0.125 × 0.125	293	99	0.49
4A	1:10	0.035 × 0.035	237	110	0.55
4B	1:10	0.05 × 0.05	185	62	0.31
5A	1:20	0.0175 × 0.0175	167	78	0.39
5B	1:20	0.025 × 0.025	131	44	0.22
6A	1:50	0.007 × 0.007	106	50	0.25
6B	1:50	0.01 × 0.01	83	28	0.14

Mesh resolution sensitivity study

The mesh size is an important factor in the CFD analyses [25]. In this case, a regular cubic grid was used in CFD simulations. The grid size must be small enough to properly model the turbulent effects. For the used LES method, a spatial resolution of 1/4 < R < 1/16 is recommended. This spatial resolution is defined as R = Δ/D*, where Δ is the element size and D* is the characteristic diameter of the plume, obtained from the Froude-number calculated as [25]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty \, c_{p,\infty} \, T_\infty \, \sqrt{g}} \right) \tag{7}$$

Figure 5 presents the results of mesh sensitivity analysis in the form of measurements of a maximum plume centerline temperature from the array of PMD, and the difference between given grid size.

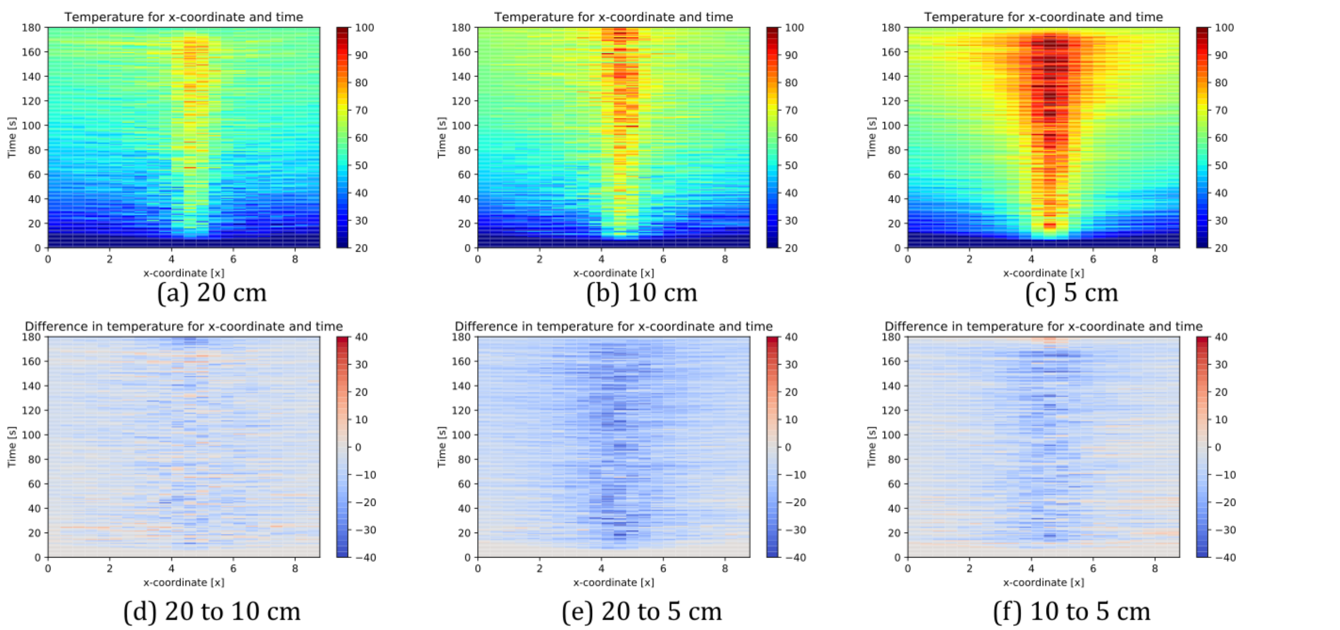


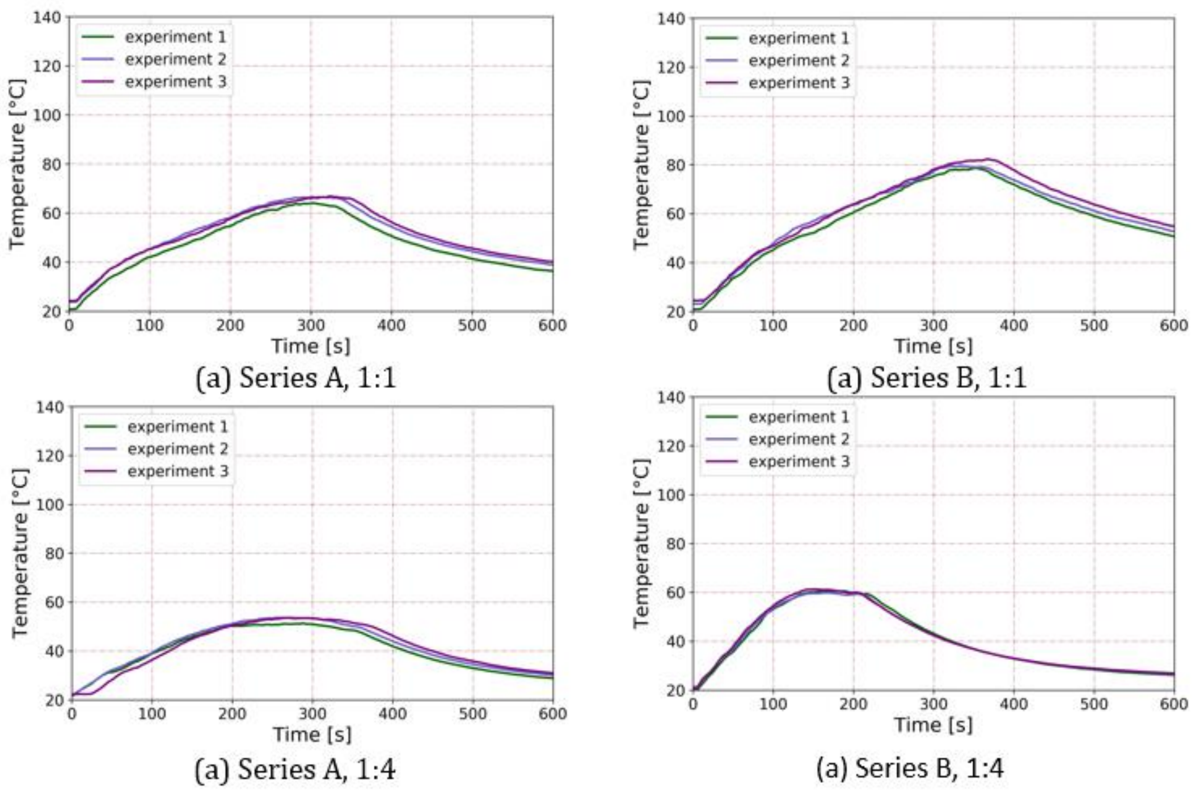
Figure 5. Comparison of results of mesh sensitivity analysis for maximum values of centerline plume temperature (a-c), and the difference between each of the grid size (d-f)

It can be noted that, the differences in the maximum centerline plume temperatures between 0.10 m and 0.05 m are much smaller, and significantly smaller than between 0.20 m and 0.10 m Based on these findings, the 5 cm mesh was chosen for further simulations. For simulations in reduced scale, the D* was maintained, and the mesh size was scaled accordingly.

RESULTS

Experimental Research

The mean temperature measured showed a good fit in terms of the shape of the temperature profile and the peak value timing (see Figures 6 and 7). The plume centerline temperatures were in good fit with the exceptions of maximum temperatures during the HRR peak. The temperatures in the middle of the compartment during cooling down period were also in good agreement. It should be noted, that expected temperatures in reduced- and full-scale should be similar if conditions for Froude-number similarity are met. To identify the source of this discrepancy, the series of numerical simulations were performed.



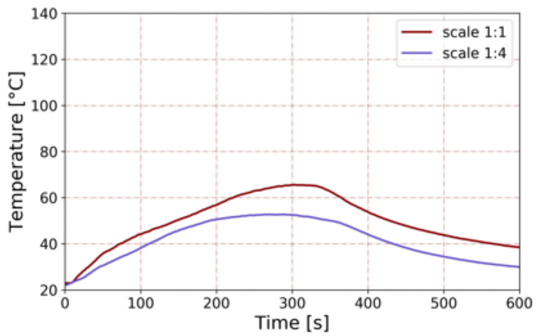
(a) Series A, 1:1

(a) Series B, 1:1

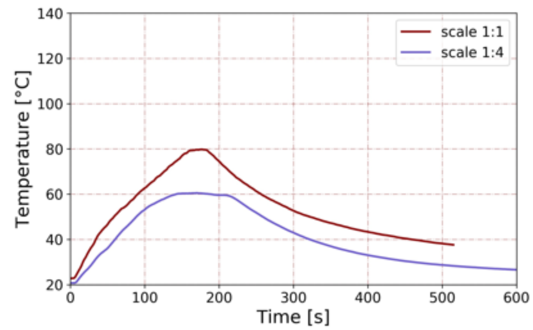
(a) Series A, 1:4

(a) Series B, 1:4

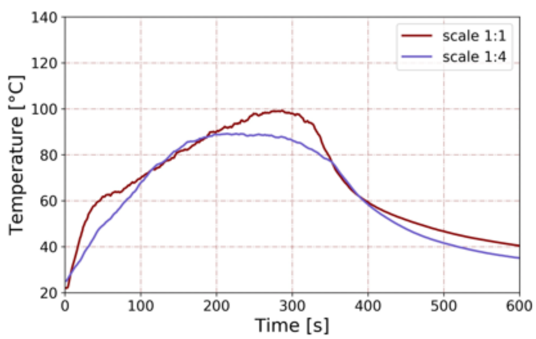
Figure 6. Mean temperature in full and reduced-scale experiment



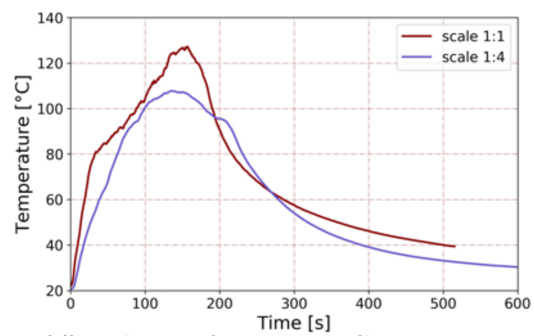
(a) Series A, mean layer temperature



(b) Series B, mean layer temperature



(c) Series A, plume centerline temperature



(d) Series B, plume centerline temperature

Figure 7. Comparison of averaged layer temperature and maximum recorded plume centerline temperatures in full and reduced-scale research

Numerical Research

The mean temperatures from the experimental research were compared with the results from CFD simulations (see Figure 8). In the first 150 s of simulations, the results for 1:1 scale were in good agreement between CFD and scale model, but further into experiment some discrepancies occurred. The temperatures in numerical analysis were lower than in experiment, with the maximum observed difference of 14°C (series B, 1:1 scale). For scale 1:4, the CFD gave higher temperature than scale model in the initial part of the experiment however in the latter part of the simulation the agreement was very good (less than 10% difference). The differences in measured temperatures between scale 1:1 and 1:4 were slightly smaller, than these observed between scales 1:1 and 1:4 in physical experiment.

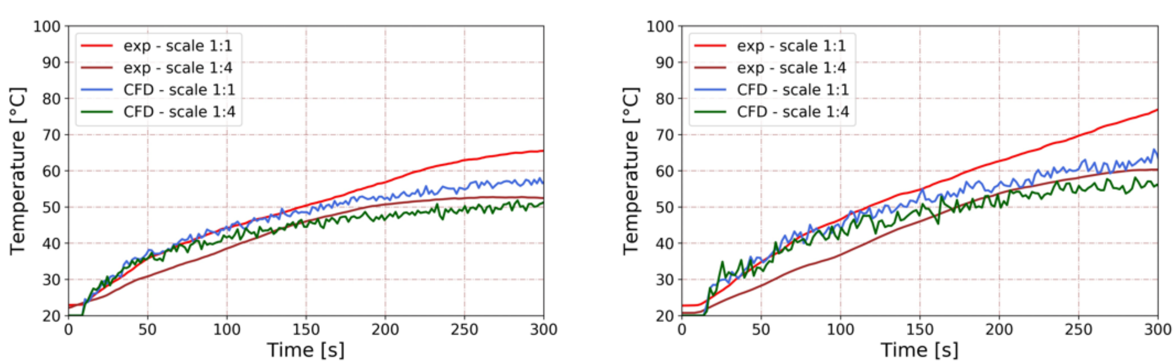
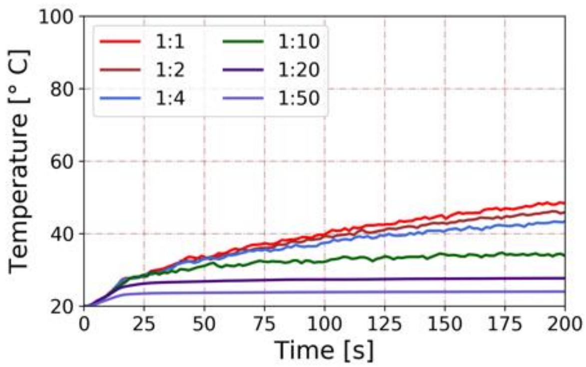
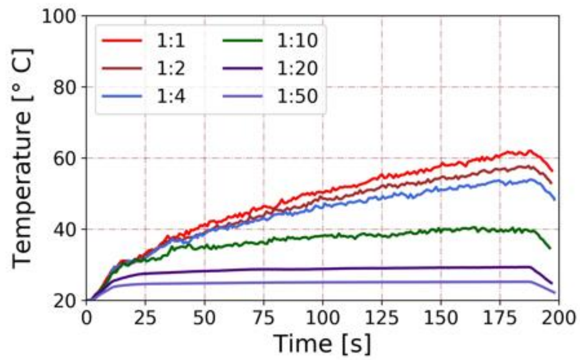


Figure 8. Comparison of the temperature measurements in experimental and CFD simulations

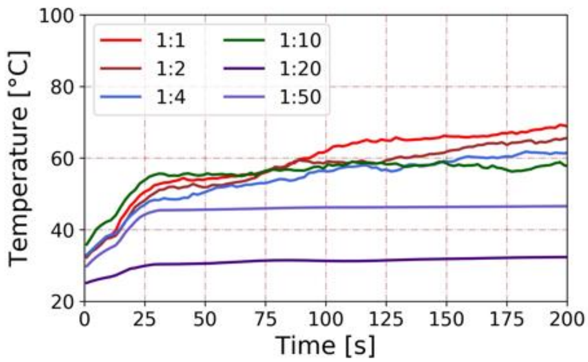
Figure 9 presents the mean smoke layer temperature for all scales investigated in the CFD analyses. As observed in the experimental part, also in the numerical calculations the mean layer temperature decreases with the scale. For scales 1:1, 1:2 and 1:4 the temperature differences are within 10% limits. The difference between 1:1 and 1:10 scale is significant, not only in the value of the temperature, but also in the temperature increment. For scale 1:1 the temperature grows in the duration of the fire, while for scale 1:10 it stabilizes around 75th second of the experiment. Similar differences were also observed for the maximum centerline plume temperature shown in Figure 9.



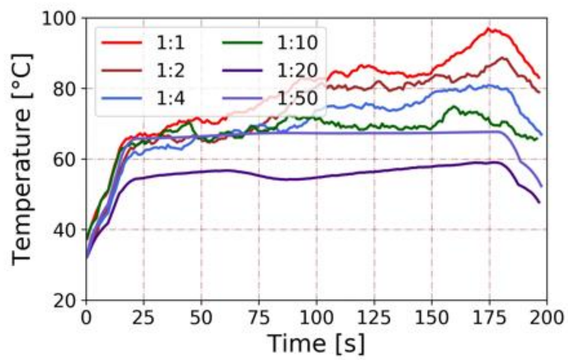
(a) Series A, mean layer temperature



(b) Series B, mean layer temperature



(c) Series A, plume centerline temperature



(d) Series B, plume centerline temperature

Figure 9. Comparison of the mean smoke layer temperature and the centerline plume temperature measurements in numerical experiments with different scales. The time value is scaled following Eq.(3)

DISCUSION

Problems with the Reynolds number

In the introduction section I have mentioned a rule of thumb that the flow turbulence should be maintained, which is closely related to the Reynolds number of the modelled flow. Quintiere mentioned, that this is usually achieved in model compartments with height > 0.3 m [27]. A simplification in this aspect is necessary, as the conservation of Froude and Reynolds numbers in the same model may be difficult. From the definition of Reynolds number

$$Re = \frac{u_0 l \rho}{\mu} \tag{8}$$

it can be noted, that scaling of the velocity or density of the fluid would invalidate the Froude similarity. Thus, if one would need to conserve the Reynolds number while following Froude relationship, it would require scaling of the kinematic viscosity of the medium, which is not practical. However, if the flow is mainly driven by the buoyancy and highly turbulent (we propose a rule of thumb value of Re > 10 000), the further increase of the Re number will have a limited effect on the fluid dynamics of the smoke plume or layer. In such case the omission of the Reynolds similarity is justified.

In practice, the flows in full fires scale are turbulent. However, once scaled down to small scale, the flow turbulence may be insufficient to justify the omission of the Reynolds scaling. In such case, the buoyant plume will not mix with surrounding air, and the entrainment will not represent the behavior of the large scale plume. Such problem was observed in the numerical experiments for scales 1:20 and 1:50, where laminar plumes were observed. The illustration of the plumes is shown in Figure 9.

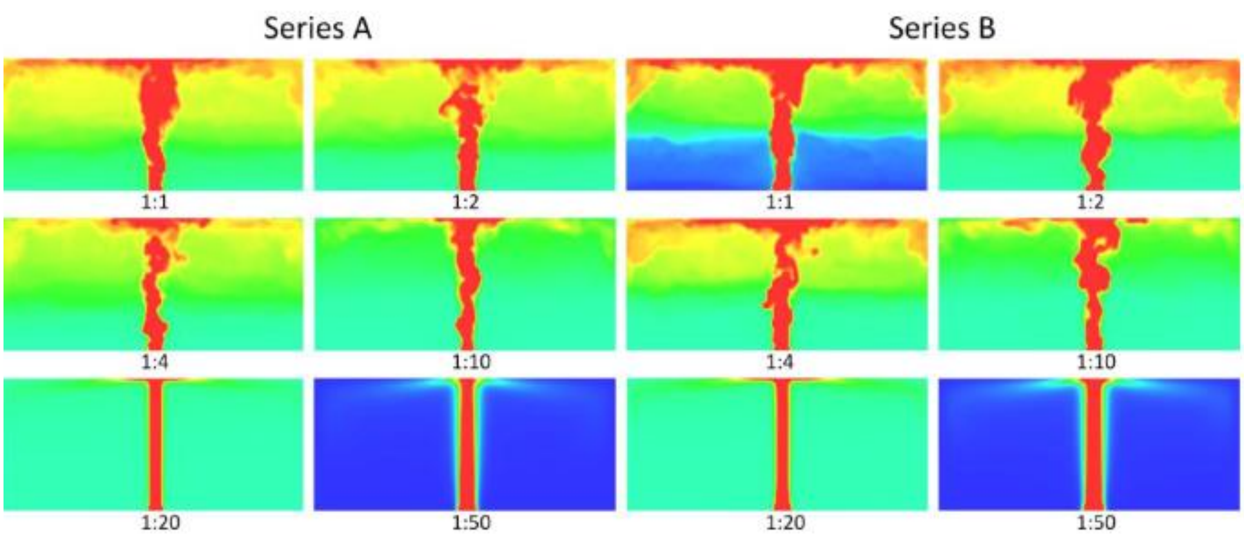


Figure 10. Temperature slice through the centerline of the smoke plume, with visible vortices forming in the plume and laminar structures in scales 1:20 and 1:50. The color scale was individually altered to illustrate the flow structure of the plume

The approximated values (for velocity averaged over 30 s) of Re number for the plume flow are shown in Table 5. The approximated Reynolds number for small scales (1:10, 1:20 and 1:50) indicates, that flow structure in these scenarios was laminar.

Table 6. The value of Reynolds number in the plume centerline

Scale	Velocity [m/s] (CFD)	Velocity [m/s] (calculated with Eq. 2)	Reynolds number (CFD)	Reynolds number (calculated)
Series A				
1:1	1.50	1.50	27 531	27 531
1:2	0.95	1.06	8 718	9 734
1:4	0.65	0.75	2 982	3441
1:10	0.40	0.47	734	871
1:20	0.05	0.34	46	308
1:50	0.08	0.21	29	78
Series B				
1:1	1.50	1.50	41 713	41 713
1:2	1.00	1.06	13 904	14 748
1:4	0.80	0.75	5562	5214
1:10	0,50	0.47	1390	1319
1:20	0.07	0.34	97	466
1:50	0.09	0.21	50	118

CONCLUSION

The paper shown observed discrepancies and problems with application of Froude-number scaling for modelling compartment fires. The experiments were performed at wide range of Reynolds numbers, showing the essential role that turbulent flow has on the temperatures in the plume and in the compartment. In case of small scales (1:2 and 1:4) the average temperatures measured were up to 30% lower than in the full scale experiment, however in most of the experiment duration this difference was up to 10% (which in opinion of the author can be considered as an acceptable value).

The temporal change in the temperature was well represented in small scale. These results indicate, that the scaling method can be useful for investigation of the flow of smoke in buildings. For smaller scales (1:10 and smaller) the differences in the temperatures measured were significant, and in case of very small scales (1:20 and 1:50) the results have no scientific value due to change of the flow from turbulent to laminar.

CFD modelling with FDS software did sufficiently represent the full- and reduced-scale experiments, and was used to analyze wide array of scaled fires. A similar approach can be used a-priori of future experiments, to verify the sensitivity of the experiment to the scale, and estimate the Reynolds number of the flow. Furthermore, the numerical modelling may help with investigating the effects of materials used in the reduced-scale model on the heat transfer to the model boundaries. To maintain the high scientific value of scaled down experiments the user should take informed decisions, and use modern tools (such as CFD modelling) to assess the model sensibility to the changes introduced in the reduced-scale.

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