Scaled models in the analysis of fire-structure interaction

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Abstract. A fire problem has been scaled both in terms of geometry, boundary conditions and materials thermophysical properties by means of dimensionless parameters. Both the full and scaled models have been solved numerically for two different fire power values. Results obtained by means of the full scale model and the scaled one are compared in terms of velocity and temperature profiles in order to assess the reliability of the scaled model to represent the behavior of the full scale one.

1. Introduction

In fire safety engineering, the prediction of fire evolution and its actions on structures can be very difficult. Several numerical models have been developed during last years, but their validation is difficult due to the lack of experimental data. This is mainly due to the complexity in carrying out experimental tests on real fire. Then, the possibility to operate with scaled experimental models could be very helpful in order to compare numerical and experimental results.

The modeling of fire evolution is very difficult due to the large number of phenomena involved, such as pyrolysis, combustion, conduction, convective and radiative heat transfer. Quintiere [1] proposed a set of dimensionless parameters to be used in fire modeling in order to make the conservation equations and the related boundary conditions dimensionless.

Several authors proposed successful scaled models in fire [2, 3] and Thomas [4, 5] and Quintiere [6] have done reviews of this topic. Chowa and Loa [7] presented a scaled model to predict smoke movement in an atrium. Full scale experiments were carried out for assessing models proposed in literature. It was found that the scaling law for temperatures proposed in literature requires further examination.

The understanding of the behavior of a structure in a fire is crucial in order to assess fire resistance requirements. Wang et al. [8] proposed a method for scaling a compartment fire. Experimental verifications at two scales were performed in order to show the validity of the proposed approach.

In this paper, the dimensionless parameters presented in [1] have been used to compare results obtained for two different models, the first one in full scale and the second one scaled by a given factor (1:2). Results are obtained numerically by means of the commercial code Ansys-Fluent. The proposed model has been scaled both in terms of geometry, boundary conditions and materials thermophysical properties by means of the aforementioned dimensionless parameters. Results obtained by means of the full scale model and the scaled one are compared in terms of velocity and...
temperature profiles in order to assess the reliability of the scaled model to represent the behavior of the full scale one.

2. Model and methodology
The analyzed problem refers to a room in which a steel beam, located on the room roof, is heated by a fire, located on the room floor. A sketch of the physical domain under investigation is shown in figure 1.

Figure 1. Sketch of the analyzed configuration.
1: IPE beam, 2: burner, 3: plasterboard walls.

A 2.48 m x 1.00 m x 2.50 m (high) parallelepiped enclosure has been taken into account. Four openings 0.60 m high are placed on the two larger vertical walls in proximity of the ceiling and the floor. The walls are made up of plasterboard, 0.020 m thick. A steel IPE beam is placed at the centerline of the ceiling.

The fire is modeled by assigning a heat flux on the portion of floor in which the fire is supposed to be located. The burner dimensions are assumed to be 2.48 m x 0.80 m x 0.08 m. The IPE beam is sketched in figure 2 and its dimensions are reported in table 1. Thermophysical properties of plasterboard, steel and air are reported in table 2.

Table 1. Dimensions of the IPE beam.

| h/mm | b/mm | a/mm | c/mm | r/mm | d/mm |
|------|------|------|------|------|------|
| 500  | 360  | 20   | 50   | 1    | 2,480 |

Figure 2. Sketch of the IPE beam.
Table 2: Thermophysical properties of materials.

| Material    | ρ/(kg m⁻³) | cp/(J kg⁻¹ K⁻¹) | k/(W m⁻¹ K⁻¹) | μ/(Pa s)   | β/K⁻¹  |
|-------------|------------|-----------------|---------------|------------|--------|
| Air         | 1.225      | 1,006           | 2.42×10⁻²     | 1.789×10⁻³ | 3.33×10⁻³ |
| Steel       | 8,030      | 502.5           | 16.3          | -          | -      |
| Plasterboard| 737        | 1,423           | 0.12          | -          | -      |

The problem has been solved numerically, by assuming gray surfaces, incompressible flow, constant thermophysical properties for solids and fluid, except for the air density, for which the ideal gas model is assumed. This latter hypothesis can be justified by taking into account that no large air temperature increase is expected, since the predominant heat transfer mechanism between the heater and the walls should be radiative heat transfer.

The governing equations for fluid and solid region, in steady state regime, are time-averaged mass, Navier-Stokes and energy equations combined with k-ε realizable turbulence model [9] and further details on the mathematical model can be found in [10].

2.1 Boundary conditions

An imposed heat flux is assigned on the burning surface depending on the fire power and the scaling factor. The openings are assumed to be black bodies at 300 K, the convective coefficient, \( h_0 \), and the temperature, \( T_0 \), outside the ceiling are assumed to be 4.0 W K⁻¹ m⁻² and 300 K, respectively. The boundary conditions for the fluid and solid domains are reported in table 3, with reference to figure 3.

![Figure 3. Boundary conditions.](image)

Table 3: Boundary conditions for the solid and fluid domains.

| Surface          | Boundary condition | Temperature |
|------------------|--------------------|-------------|
| Outside ceiling  | \( -k \frac{\partial T}{\partial y} = h_0 (T_{in} - T_0) \) | 300 K       |
| Vents            | \( \frac{\partial u}{\partial x} = 0 \), \( \frac{\partial v}{\partial x} = 0 \), \( \frac{\partial w}{\partial x} = 0 \) | 300 K       |
| Vertical walls   | 0                  | 300 K       |
| Outside floor    | 0                  | 300 K       |
2.2 Scaling and dimensionless parameters
Dimensionless parameter, to be used for scaling models, will be obtained from the conservation equations.
As for the velocity, by making reference to conservation of momentum equation in the hypothesis of natural convection, it is possible to obtain a normalizing factor for velocity equal to [1]:

\[ \bar{u} = \sqrt{gl} \]  

(1)

where \( g \) is the acceleration due to the gravity and \( l \) is a characteristic length for the analyzed problem. The dimensionless group for scaling firepower is [1]:

\[ \dot{Q}^* = \frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g} l^{5/2}} \]  

(2)

By denoting with the subscript “s” variables for the scaled model and “f” the ones for the full model, the aforementioned dimensionless group allows evaluating the firepower for the scaled model as:

\[ \dot{Q}_s = \dot{Q}_f \left( \frac{l_s}{l_f} \right)^{5/2} \]  

(3)

where \( l_s \) and \( l_f \) are characteristic length for scaled and full model and then their ratio represents the geometric scaling factor.

It is worth noticing that temperature values are scaled with respect to the ambient temperature, \( T_\infty \), then, by assuming this latter unchanged between the scaled and full models, it follows that expected temperature values will be the same for the two models, for both gaseous and solid domains.

The following dimensionless number allows to scale heat conduction within walls [1]:

\[ \dot{Q}_k^* = \frac{(k \rho c_p)^{1/2}_{w}}{\rho_\infty c_p g^{1/4} l^{3/4}} \]  

(4)

The previous parameter allows to evaluate the scaled wall thermal conductivity, \( k_s \), as:

\[ k_s = \left( \frac{l_s}{l_f} \right)^{3/2} k_f \]  

(5)

2.3 Numerical analysis
The commercial Fluent CFD code was employed to solve the governing equations [9]. The SIMPLE scheme was chosen to couple pressure and velocity. The Discrete Transfer Radiation Model (DTRM), that assumes all surfaces to be diffuse, is chosen. The following convergence criteria were assumed: \( 10^{-3} \) for the residuals of the velocity components and \( 10^{-8} \) for the residuals of the energy. An analysis of sensitivity was conducted in terms of temperature profiles; a 120° polar angle and a 48° azimuthal angle were chosen for the radiation model as well as a 0.010 m square grid was chosen for the thermo-fluid-dynamic model.
3. Results
In order to assess the reliability of the aforementioned parameters to be used as scaling parameters for
the proposed fire model, a comparison between temperature and velocity profiles for the problem
presented in the previous section and the ones obtained for a scaled model has been carried out. A
geometric scaling factor equal to 0.5 (1:2) has been assumed. Once the problem has been scaled
geometrically, scaled firepower and wall thermal conductivity are evaluated by means of equations (3)
and (5). Comparison has been carried out in terms of temperature profiles, not scaled for both models,
and velocity profiles; in this latter case velocity values for the scaled model are scaled by means of the
normalization factor reported in equation (1). Two firepower values for the unscaled model are
assumed, 100 kW and 200 kW. Temperature and velocity profiles have been presented in terms of the
dimensionless spatial variables X, Y and Z, by assuming a normalizing factor equal to the
computational domain length along the x, y and z direction, respectively.
In figure 4 Z planes and Y values, at which results will be presented, are reported. Moreover, surface
beam temperature profiles on the faces indicated with A and B in figure 5 will be presented.

Figures 4. Sketch of the planes at which results will be presented.

Figures 5. Sketch of the beam sides at which results will be presented.
The comparison between air temperature profiles along \( x/L \) axis for full and scaled models for a firepower value equal to 100 kW is presented in figure 6 for several \( Z \) and \( Y \) values. For \( Y=0.24 \) air temperature differences between full and scaled models are less than 5 K, with a maximum percentage difference of about 15%. Differences between predicted temperature values for the two models increase with \( Z \) that is from the boundary of the domain along \( z \) axis to the center of the same. For \( Y=0.72 \) temperature differences are lower than for \( Y=0.24 \), except for \( Z=0.128 \) in proximity of the domain walls (\( x/L \) values near zero), where differences between temperature predicted by the two analyzed models are about 15 K, with a maximum percentage difference equal to about 30%. For the others analyzed \( Z \) values, percentage differences are less than 10%.

In figure 7 beam wall temperature profiles along \( A \) and \( B \) side showed in figure 5 are reported for the full and scaled models for the same \( Z \) values analyzed in the previous figure. As for the horizontal wall, side \( A \), both models predict wall temperature values increasing with \( Z \) increase. Large differences between temperature values from full and scaled models are detected, with a maximum percentage difference of about 30%. Similar considerations can be made for the analyzed vertical beam wall, side \( B \), shown in figure 7b. In this case maximum percentage discrepancy between the two models is about 35%. These results suggest that a more accurate scaling procedure has to be accomplished as for the conjugate heat transfer between air and beam, by taking into account scaling factors not only for heat conduction in the walls, but also for convective and radiative heat exchange.

![Figure 6](image1.png)

**Figure 6.** Air temperature profiles along \( x/L \) axis for a firepower equal to 100 kW, for several \( Z \) values and for \( Y=0.24 \) (a) and \( Y=0.72 \) (b).

![Figure 7](image2.png)

**Figure 7.** Beam wall temperature profiles along \( x/L \) axis for a firepower equal to 100 kW, for several \( Z \) values on side \( A \) (a) and \( B \) (b).
The comparison between air velocity profiles predicted by full and scaled models, along x/L axis, for several Y and Z values and for a fire power equal to 100 kW is reported in figures 8 and 9. The y velocity component is reported in figure 8, whereas the velocity magnitude is reported in figure 9. For Y=0.24, figure 8a shows y velocity component profiles almost overlapped for full and scaled models for Z=0.128. Differences between two models increase as Z increases, the maximum percentage difference being about 40% for Z=0.496 and for low x values. Differences between the two models decrease as x increases, where the influence of the domain walls diminishes. A similar behavior is exhibited at Y=0.72, figure 8b. In this case differences are lower than the ones detected for Y=0.24, except for Z=0.128 and in proximity of the domain walls. For all other Z values, maximum percentage difference is about 20%. As for velocity magnitude, figure 9 shows that maximum percentage difference between air velocity magnitude values predicted by the two analyzed models are about 30% and 20% for Y=0.24 and 0.72, respectively. Also in this case maximum differences are attained in proximity of the domain walls.

Similar temperature profiles reported in figures 6-7 for a fire power equal to 100 kW, are reported in figures 10-11 for a fire power equal to 200 kW.

The comparison between air temperature profiles along x/L axis for full and scaled models for a firepower value equal to 200 kW is presented in figure 10 for several Z and Y values. By comparing these temperature profiles with the ones reported in figure 6 for a firepower equal to 100 kW, it can be observed a similar trend, with expected larger temperature values for the 200 kW case. The maximum percentage difference between temperature values predicted by full and scaled models is about 15% for both analyzed Y values.

![Figure 8](image1)

**Figure 8.** Air y velocity component profiles along x/L axis for a firepower equal to 100 kW, for several Z values and for Y=0.24 (a) and Y=0.72 (b).

![Figure 9](image2)

**Figure 9.** Air velocity magnitude profiles along x/L axis for a fire power equal to 100 kW, for several Z values and for Y=0.24 (a) and Y=0.72 (b).
In figure 11 beam wall temperature profiles along A and B side showed in figure 5 are reported for the full and scaled models for the same Z values analyzed in the previous figure for a firepower equal to 200 kW. Also in this case similar trends as those observed in figure 7 are observed and temperature values are obviously larger. Maximum percentage differences between the two models are about 30% and 25% for side A and B, respectively.

**Figure 10.** Air temperature profiles along x/L axis for a firepower equal to 200 kW, for several Z values and for Y=0.24 (a) and Y=0.72 (b).

**Figure 11.** Beam wall temperature profiles along x/L axis for a firepower equal to 200 kW, for several Z values on side A (a) and B (b).

The comparison between results for full and scaled models, for all the analyzed cases, shows a better agreement for the air temperature and velocity profiles than for the beam wall temperature profiles. Moreover, the agreement for air temperature and velocity profiles worsens in proximity of the beam walls. This analysis shows that the chosen scaling parameters don’t allow a good scaling of the model as for the heat exchange between the beam and the fire compartment, thus indicating that other scaling parameters have to be used, in order to account for convective and radiative heat transfer.

### 4. Conclusions

A method to scale a compartment fire problem was presented. Dimensionless parameters were identified in order to scale the model in terms of geometry, boundary conditions and materials thermophysical problems. Both the full and scaled models were solved numerically for two different firepower values. Results obtained from the full scale model and the scaled one were compared in
terms of velocity and temperature profiles in order to assess the reliability of the scaled model to represent the behavior of the full scale one. Differences between the full and scaled models were large in proximity of the domain walls, whereas they decreased moving away from the walls. Results suggested that a more accurate scaling procedure was to be accomplished as for the conjugate heat transfer between air and domain walls, by taking into account scaling factors not only for heat conduction in the walls, but also for convective and radiative heat exchange.

5. Nomenclature

- $c_p$: Specific heat
- $g$: Acceleration due to the gravity
- $h$: Convective heat transfer coefficient
- $k$: Thermal conductivity
- $l$: Characteristic length
- $Q$: Fire power
- $T$: Temperature
- $X, Y, Z$: Dimensionless Cartesian coordinate
- $x, y, z$: Cartesian coordinate
- $u, v, w$: Velocity component
- $\beta$: Thermal expansion coefficient
- $\mu$: Viscosity

**Superscript**
- $*$: Dimensionless

**Subscripts**
- $0$: Ambient
- $f$: Full
- $k$: Conductive
- $P$: Ceiling external surface
- $s$: Scaled
- $w$: Wall
- $\infty$: Refers to ambient value

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