Validation of an Enthalpy Scaling Method for Thermally Driven Building Flows

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Abstract

An approach combining scale modeling and PIV technology provides a reliable method for scaling thermally driven flows. The technique combines greater flexibility than prescriptive methods with a theoretical approach that is more easily understood than widely used computational tools. The approach is validated through comparison with a well-known study of doorway opening flow coefficients for room fires. This method has the potential to be developed as a widely accepted and applied approach to smoke and air movement analysis in support of building design, CFD validation or forensic analysis. Work in progress is applying the method to scale analysis of Underfloor Air Distribution (UFAD) technology and natural ventilation schemes.

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1. Introduction

Understanding and predicting fluid flows is a complex subject within engineering which is made even more difficult by the fact that it can be very complicated to visualize fluid flow with the naked eye. When designing a building, a number of experts are required to conduct fluid flow analysis to ensure and confirm the proper design of Heating Ventilating Air Conditioning (HVAC), environmental ventilation, and smoke and fire management systems. The analyses and reports are difficult to understand because they incorporate very complex engineering principles that a general engineer, architect or fire department inspector may have trouble understanding. There is demand for an evaluation method of thermally driven building fluid flows that is comprehensive from an engineering standpoint, but also simple to understand and interpret for a non-engineering specialist. The method would be useful for a number of different uses including: HVAC flow verification, testing of smoke removal systems, and general ventilation flow visualization within building models.

Specialists now rely on design guides and regulatory documents, analytical expressions, and experimental correlations, to design safe, comfortable and energy efficient buildings. Increasingly they are also being asked to evaluate complicated computational modeling techniques without an understanding of the physics employed in these models. Typical users might include architects, HVAC engineers, fire protection engineers, forensic investigators and authorities having jurisdiction (AHJ). AHJ are working for the state or local government whose job is to review all tests and analysis conducted by engineers and architects to prove that all aspects of the building design meet building codes.

Scale modeling techniques are not new; salt water modeling placed an inverted scale representation of an architectural space into a fresh water tank. More dense salt water was inserted to represent smoke and as it sank provided a representation of how smoke or air movement is driven by buoyant forces. Techniques and rules developed for this type of modeling provide a transition to this new technique that may enhance adoption by specialists who are more comfortable with a physical model than one created in the virtual space of a computer.

This work is related to scaling approaches like salt water modeling that saw wide and effective use prior to development of CFD tools and can be employed as a supplement analytic expressions and computer modeling programs. The scaled PIV experiment uses natural laws and real physics scaled using simple expressions from simplified equations governing heat transfer and fluid mechanics. While there opportunity to misinterpret the results of scaled model testing, the approach provides fewer avenues to alter or incorrectly describe or interpret the governing physics of the model as is frequently the case in CFD approaches. The expectation is that this relative transparency and ease of use will encourage use of modeling approaches to enhance design flexibility while lowering costs.

The project combined enthalpy scaling methods with simple measurements of temperature and gas velocity to provide an improved method for fluid analysis in small scale building models. Particle image velocimetry (PIV) was applied as an enhancement to the approach but is not required to provide the results shown in this work. Scaling methods were taken from basic heat transfer and combustion principles widely available in the literature and design guides [1].

In fire protection engineering, scaling methods are given detailed treatment in regulatory documents, which list the scaling expressions and provide guidance on their use [2]. The scaling rules used in the experiment were implemented in selection of the scaled heat release rate as well as the dimensions of the building. Fluid flows were visualized using both anemometry and Particle Image Velocimetry (PIV). PIV is a tool which takes quick successive pictures of a particle seeded flow field illuminated by laser light. Software is used to analyze and track particles in the flow in order to determine their velocities.

2. Experimental methods

1) Apparatus

Room dimensions were selected to match (at reduced scale) the dimensions of a larger scale experiment which measured door inflow and outflow coefficients for a series of fire sizes and door dimensions [1].The project is comprised of a small (1/7.27) scale model room mounted on an optical table dimensioned as shown in Figure 1 with a doorway opening 0.252 m high and of variable width (W_o). The door was located in the center-line of one wall. The height of the doorway opening of the room was fixed at 25.2 cm but the width was varied from 3.2 to 12.4 cm which means a door width ranging from 23 to 90 cm in full scale. For each width, the heat of the natural gas burner was controlled and ranged from 50 kW to 150 kW. For all the experiences, the room was heated up during 20 to 30 minutes until a stable temperature was reached. The measurements were done after obtaining that steady state.

The walls, ceiling and floor of the room were 5/16th inch drywall. A 4.2 cm diameter natural gas burner provided a scaled heat source designed to simulate a room fire.

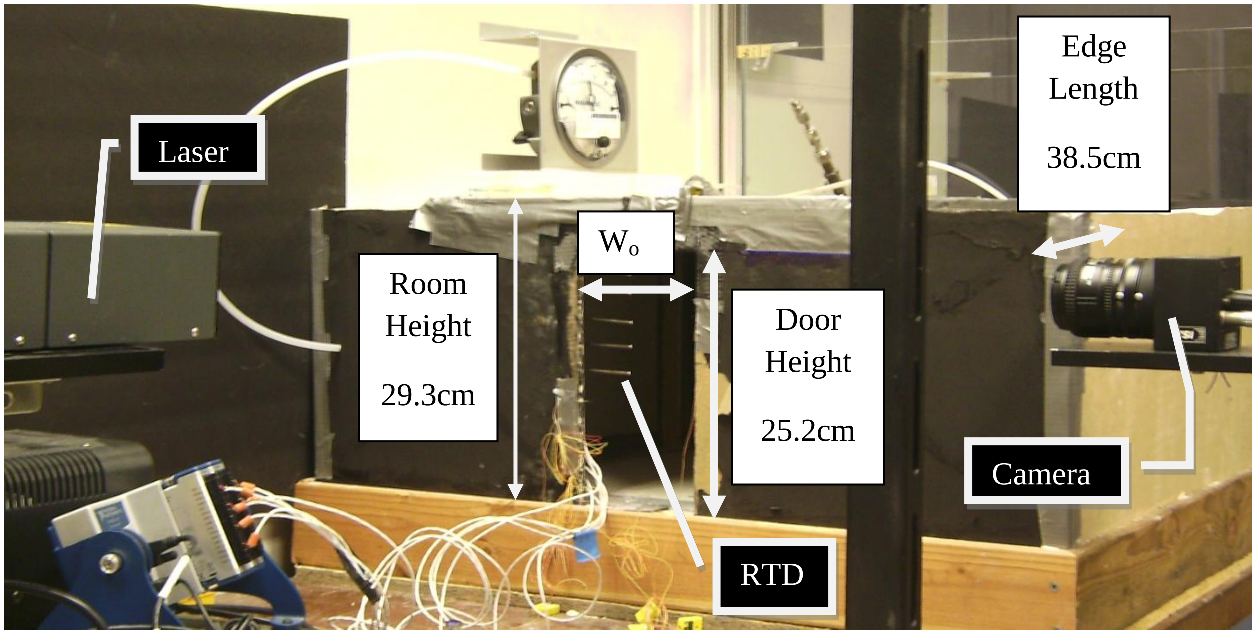

Figure 1. Picture of the setup

Tracer particles were introduced to follow the flow streamlines through the doors. The space is visualized with a TSI Particle Image Velocimetry system comprised of a laser and its power source, a tripod mounted camera and a synchronizer.

2) Measurements

a) Temperature

Flow temperatures were measured with a set of resistance thermometric devices (RTD's) place in a vertical tree configuration at the door opening of the room and with thermocouples outside the room. Vertical separation of the RTD's was 2.54 cm. RTD's provide very accurate measurements of small differences in gas temperature. The measurements were corrected for flame radiation from the burner.

b) Velocity

A hot wire anemometer was used to measure the inflow velocity throughout the door opening at different heights. The outflow velocity was measured with the PIV since high gas temperatures made the anemometry technique unreliable.

c) Flow Visualization

The flow movement was visualized using particle image velocimetry. An Nd YAG laser which emits a wavelength at a frequency of 532 nm at100 mJ of power is focused as a thin sheet and illuminates a plane of particles in the domain. Two short pulses of green laser light, separated in time by a few milliseconds illuminate tracer particles which scatter the light for detection by a high speed CCD camera. The two images are analyzed using software that provides a measure of the local fluid velocity.

A component necessary for the success of the PIV system is the tracer particle and its seeding system. Two kind of seeding were used: a fog created by a theatrical fog maker and titanium dioxide particles (TiO_2). The particles have to fulfill two requirements: following the motion of the fluid and having good light scattering characteristics. These two conditions are in opposition with each other. A big particle scatters more light but more inertia that inhibits movement with the flow. A small particle is better at following the flow but doesn't scatter as much light.

To ensure the first requirement, a comparison between the settling velocity of the particle under gravity and the actual flow velocity is necessary [3]. It is assumed that Stokes drag governed the process; the settling velocity u_∞ is given by:

$$u_\infty = \frac{g d_p^2 \left(\rho_p - \rho_f\right)}{18\mu} \tag{1}$$

The particles are considered suitable as long as this velocity is negligible compared to the actual flow velocity.

	Diameter particle (m)	Volumetric mass particle (kg/m³)	Settling velocity (m/s)	Mean flow velocity (m/s)	References
Fog (propylene glycol)[1]	$4.958*10^{-9}$	1.25	$3.7*10^{-14}$	0.4	[4]
TiO_2	$1*10^{-6}$	3500	$1.215*10^{-4}$	0.4	[5]

Table 1. Selection criteria for particles

[1] The fog is obtained by heating up water and propylene glycol based fluid. For the calculations, we considered the fog is only formed of propylene glycol.

3. Approach

a) Scale modeling

Maintenance of the ratio between momentum and viscous forces, through application of Reynolds number similarity, has been used for decades to develop scale models for evaluation of fluid flows over solid objects. By maintaining Reynolds number similarity, visualization of resultant fluid flows in scale models maintains the flow features expected in the larger objects.

Introduction of a simulated scale model fire and resultant buoyant flows adds an element to the scale model that must be accounted for with similar scaling techniques. Prior work on scaling of buoyant plumes maintained the ratio between fire power and enthalpy flow in the plume through dimensional analysis of the energy equation. [6] This approach assures that a scaled temperature is seen at homologous times and locations in the model as in the prototype. A scaling ratio of 7.27 was chosen to give the model a full scale height of 29.3 centimeters. Room architecture was chosen to match the experiments of Quintiere [7] so that the technique could be validated against this work. A non-dimensional analysis was conducted for the scaling of the heat release. The scaled heat release rates were to be achieved by altering fuel flow rates to a 4.2 centimeters burner. Using the ratio of fire power to enthalpy flow as our similarity variable, the non-dimensional heat release rate equation used was:

$$Q^* = \frac{\dot{Q}}{\rho_o\, c_p\, T_o\, g^{\frac{1}{2}}\, l^{\frac{5}{2}}} \tag{2}$$

which is commonly referred to as the Zukoski number. By varying Q in the scaled model, it was possible to test different sized fires ranging from a total heat release rate of 50 kW to 150 kW. By preserving the scaling relationships of equation (2), it was possible to maintain the same temperatures at the same points at the same times within the model and prototype. This preservation was achieved through the recognition of the relation between heat release rate and the scaled length as shown in equation (3):

$$\dot{Q} \sim l^{\frac{5}{2}} \tag{3}$$

By utilizing the relation in equation (3), the heat release of the model was found with respect to the length scaling ratio and the prototype heat release rate. [1, 8]

$$\dot{Q}_m = \dot{Q}_p \left(\frac{l_m}{l_p}\right)^{\frac{5}{2}} \tag{4}$$

With the model fire heat release calculated, the flow rate of gas could be computed. Using natural gas to fuel the burner with an assumed heat of combustion of 54,4 kJ/g and an assumed a density of 0.8 kg/m3, the scaled down fire size was computed using equation (4) to calculate the flow rate of gas in cc/min.

$$Q = \frac{\frac{\dot{Q_m}}{HOC}}{\rho} \tag{5}$$

To control the flow of gas, a Matheson model 603 rotameter was used. The specific rotameter was designed for use with methane, but the chemical make-up of natural gas consists primarily of methane so it was a suitable substitute.

Finally, it was necessary to make sure that the physical size of the burner used in the model was a reasonably accurate size for a scale fire given the heat release rate of 215 kW/m^2 and a fire size range of 50 to 150 kW. This was done by dividing the fire size by the heat release rate, to get an area. Then a radius was determined from the area, and using the scaling value of 1:7.27, a radius was determined for the small scale model. The radii ranged from 3.7 cm to 6.5 cm, with a burner radius of 4.2cm it was assumed this was a realistic size. The values of full and reduced scale heat release rates, flow rates and fire size are given in table 1 below.

Large scale fire size (kW)	Small scale fire size (W)	NG flow rate (cc/min)	Large scale fire area (m^2)	Large scale fire radius (m)	Small scale fire radius (cm)
50	350.9	483.7	0.233	0.27	3.74
63	442.1	609.5	0.293	0.31	4.20
80	561.4	774	0.372	0.34	4.73
100	701.7	967.4	0.465	0.38	5.29
150	1052.6	1451.2	0.698	0.47	6.48

Table 2. Equivalence between full and small scale

b) Flow coefficient

To obtain outflow and inflow coefficients, respectively C_o and C_i, the ratio of actual to theoretical mass flow rates were calculated. The temperature, pressure and velocity measurements at the doorway were used to obtain actual or experimental mass flow rates defined by the relations:

$$\dot{m}_{ia} = \int_0^{W_o} \int_{Z_s}^{Z_n} \rho v \, dz \, dy \tag{6a}$$

$$\dot{m}_{oa} = \int_0^{W_o} \int_{Z_n}^{Z_o} \rho v \, dz \, dy \tag{6b}$$

where the first subscripts i and o refer to inflow and outflow and the second subscripts a and i refer to actual and ideal. W_o is the opening width, Z_s the sill height, Z_n the neutral plane height and Z_o the soffit height.

The theoretical or idealized mass flow rates were obtained from the static pressure ideal gas flow model of Quintiere and Denbraven [9]:

$$\dot{m}_{ii} = W_o \, \rho_a \, T_a \int_{Z_s}^{Z_n} \left[(2g/T_o) \int_{z}^{Z_n} \left({}^{1}\!/_{T_{or}} - {}^{1}\!/_{T} \right) dz' \right]^{\frac{1}{2}} dz \tag{7a}$$

$$\dot{m}_{oi} = W_o \, \rho_a \, T_a \int_{Z_n}^{Z_o} \left[(2g/T_o) \int_{Z_n}^{z} \left({}^{1}\!/_{T_{or}} - {}^{1}\!/_{T} \right) dz' \right]^{\frac{1}{2}} dz \tag{7b}$$

where $\rho_a T_a$ is a constant by ideal gas law, g the gravitational acceleration, T the temperature in the test room, T_{or} the temperature outside and T_o the horizontally averaged temperatures in the opening.

The coefficients were defined as:

$$C_o = \dot{m}_{oa} / \dot{m}_{oi}$$

$$C_i = \dot{m}_{ia} / \dot{m}_{ii}$$

4. Results

a) Temperature

Figure 2 shows temperatures taken at the door of the scaled room (left) and for the experiments of Quintiere (right) for varying door widths. The scaled room fire matches that of the larger scale experiments.

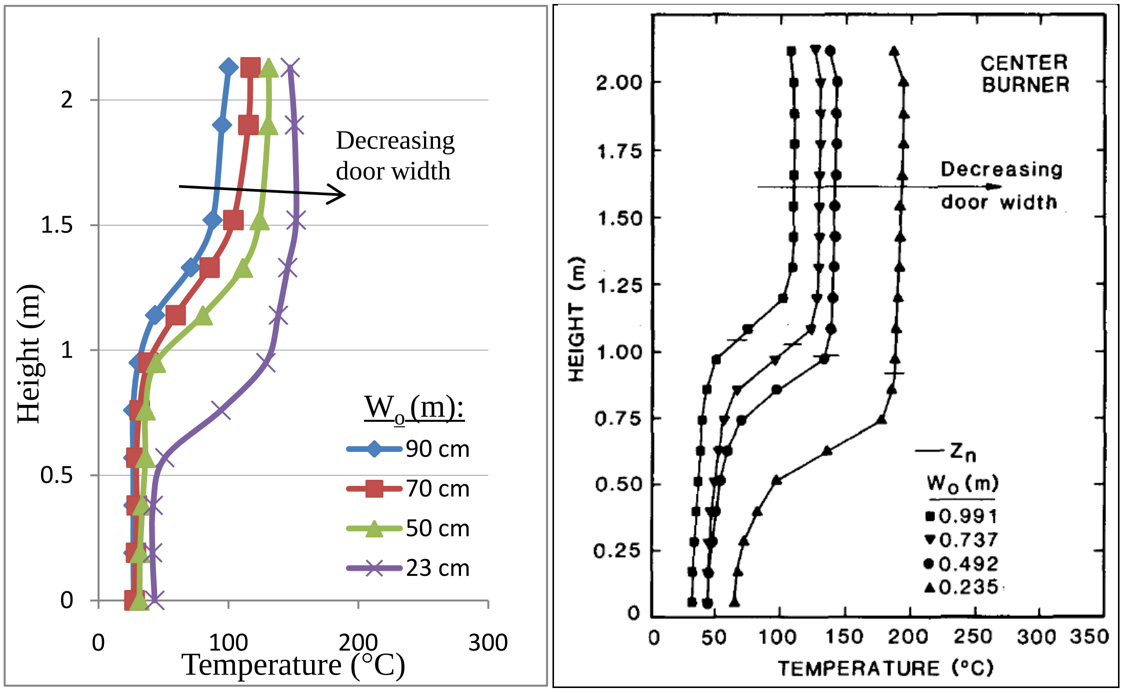

Figure 2. Vertical temperature profiles in the room at 63 kW for a center burner.

b) Neutral plane

The height of the neutral plane in the doorway was found using velocity measurements and PIV imagery. Fig. 4 illustrates the dependency of the neutral plane height on the door width and the fire strength. When the fire gets larger and the width smaller, the neutral plane height lowers.

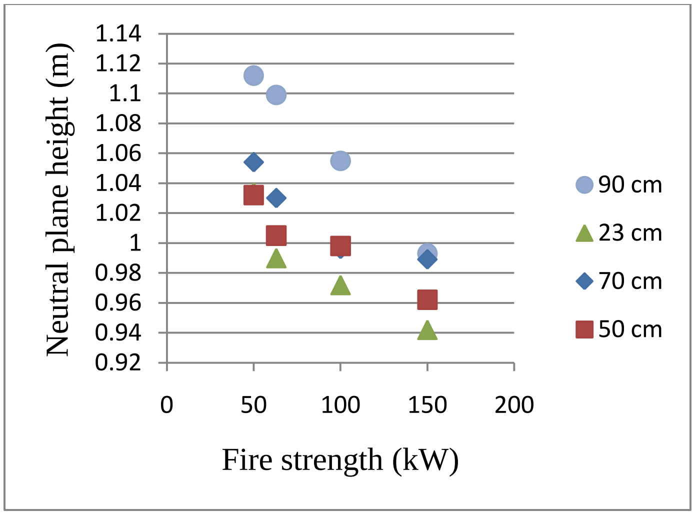

Figure 3. Influence of door width and fire strength on the neutral plane height.

c) Flow coefficients

Figures 4 and 5 below show the experimental flow coefficients through the door for the scaled room (left) and for the experiments of Quintiere (right). The scaled room fire matches that of the larger scale experiments. For the small fires (50 and 63 kW), inflow and outflow coefficients are smaller than those found by Quintiere. One explanation is that for the small scale experiments, the relatively large anemometer to door width ratio may influence the flow creating a disturbance in the flow, which can explain the smaller velocities and smaller coefficients. For the largest fires (100 and 150 kW), flow coefficients in the small scale matched full scale coefficients.

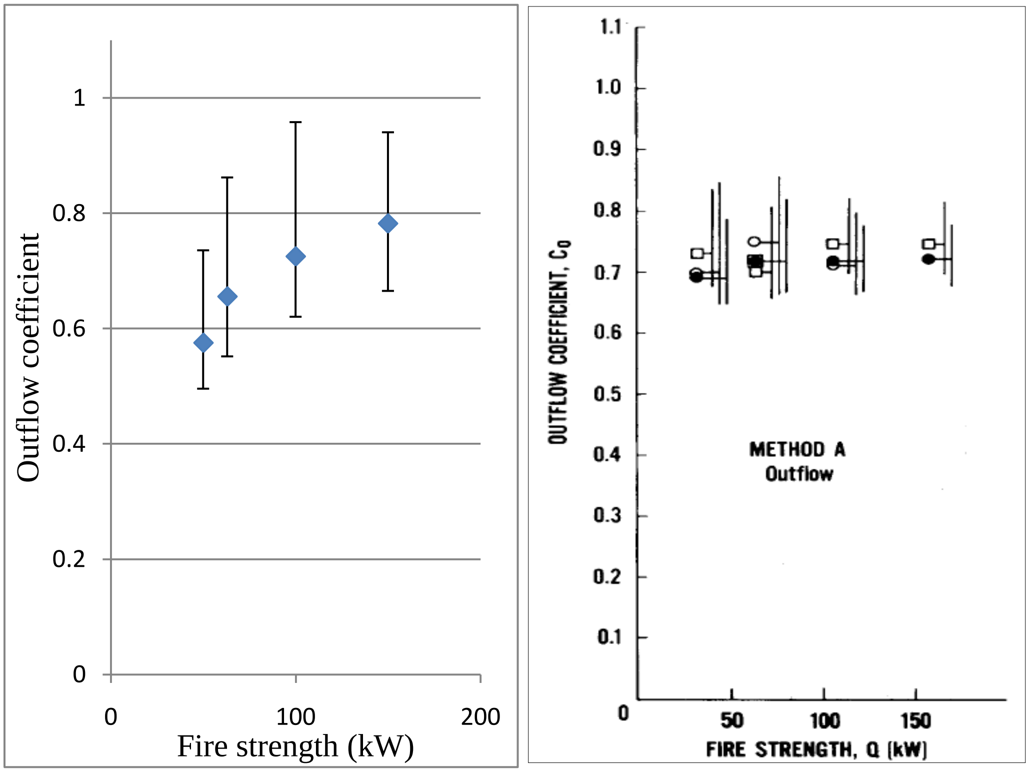

Figure 4. Experimental outflow coefficient as a function of fire strength

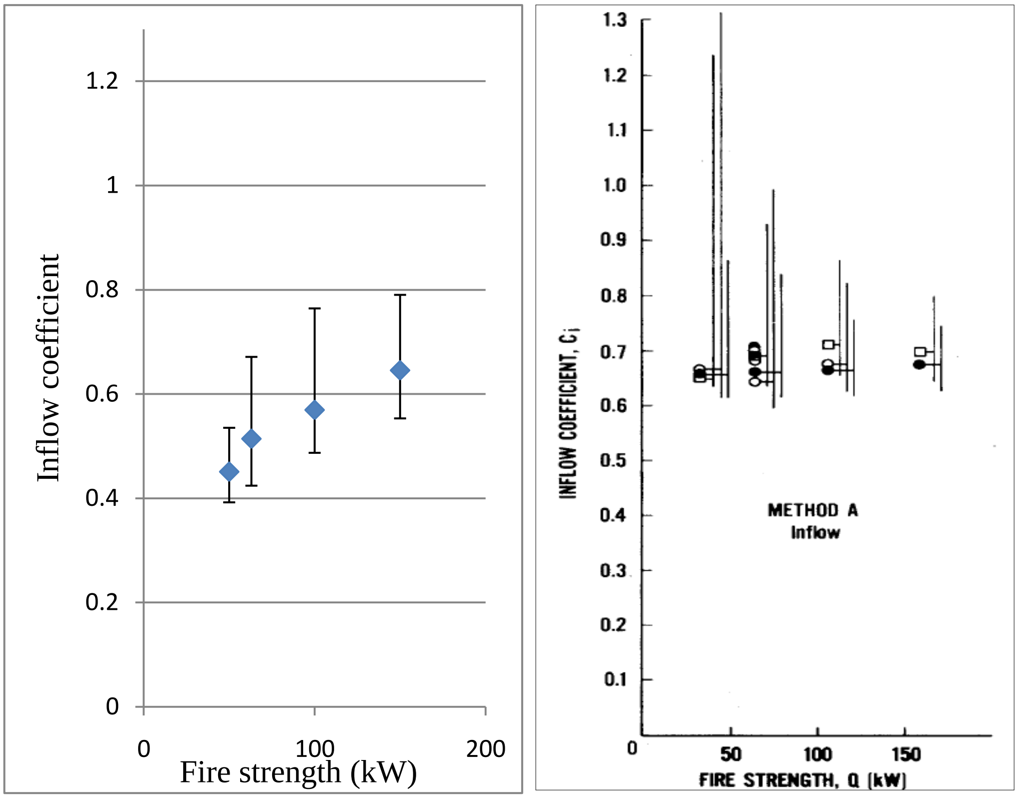

Figure 5. Experimental inflow coefficients as a function of fire strength.

5. Conclusion

This study showed that the combination of scale modeling and PIV technology provides a reliable method for scaling thermally driven flows through comparison with a well-known study of doorway opening flow coefficients for room fires. The results in terms of temperature and neutral plane height matched the results of Steckler and Quintiere experiments [7].Flow coefficients found using the scale model provide reasonably good agreement with larger scale results. Some improvements to this preliminary effort that could provide better agreement between the small and large scale results include minimizing interactions with the surrounding environment as ventilation or tools wires, changing the walls material or improving measurements. This has the potential to be developed as a widely accepted and applied approach to smoke and air movement analysis in support of building design, CFD validation or forensic analysis. Work in progress is applying the method to scale analysis of Underfloor Air Distribution (UFAD) technology and natural ventilation schemes.

6. References

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