Høgskulen på Vestlandet

Master Thesis

ING5002

Predefinert informasjon

Startdato:	25-05-2019 09:00	**Termin:**	2019 VÅR
Sluttdato:	03-06-2019 14:00	**Vurderingsform:**	Norsk 6-trinns skala (A-F)
Eksamensform:	Masteroppgave		
SIS-kode:	203 ING5002 1 MOPPG 2019 VÅR Haugesund		
Intern sensor:	(Anonymisert)		

Deltaker

Kandidatnr.: 103

Informasjon fra deltaker

Engelsk tittel *: Experimental study of the effect of Froude-number scaling on radiation

Egenerklæring *:	Ja	**Inneholder besvarelsen konfidensiell materiale?:**	Nei
Jeg bekrefter at jeg har registrert oppgavetittelen på norsk og engelsk i StudentWeb og vet at denne vil stå på vitnemålet mitt *:	Ja		

Jeg godkjenner autalen om publisering av masteroppgaven min *

Ja

Er masteroppgaven skrevet som del av et større forskningsprosjekt ved HVL? *

Nei

Er masteroppgaven skrevet ved bedrift/virksomhet i næringsliv eller offentlig sektor? *

Nei

Høgskulen på Vestlandet

MASTEROPPGAVE

Studie av effekten til Froude-tall skalering på stråling

Experimental study of the effect of Froude-number scaling on radiation

Daniel Stavland Kinden

Brannsikkerhet

Høgskulen på Vestlandet

03.06.19

Jeg bekrefter at arbeidet er selvstendig utarbeidet, og at referanser/kildehenvisninger til alle

kilder som er brukt i arbeidet er oppgitt, *jf. Forskrift om studium og eksamen ved Høgskulen på Vestlandet, § 10.*

SUMMARY

Froude-scaling is a widely used tool in fire safety analysis, this is used to reduce the cost and to simplify large scenarios in order to study them more efficiently.

This study aims to investigate the limitations of downscaling, specifically when it comes to radiation. No previous work has been found on this subject, apart from the initial conclusion that Froude-scaling has limitations regarding radiation.

It appears from this study that the more downscaling that happens the bigger impact it has on the underestimation of radiation. An error of 49-87% is present in this study. This will have an effect on the results of a study, specifically studies regarding fire safety. Both the experiments conducted in this study, and the numerical calculations show the same trend of underestimation.

CONTENTS

List of tables

List of figures

1 INTRODUCTION

1.1 BACKGROUND

This thesis is based upon earlier findings in the bachelor thesis "Numerical study of downscaling the Runehamar tunnel fire test". When scaling down a tunnel fire using Froude scaling a discrepancy was found regarding radiation. The expected radiation was severely underestimated the more the experiment was scaled down.

Considering that scaling is widely used in the fire safety community, it is important to shed light on discrepancies regarding this method. [1]

1.2 OBJECTIVE

As such, it was desirable to further study the effect that Froude scaling had on radiation.

How severe is the underestimation on radiation using Froude scaling.?

Does this have a consequence for fire safety research using Froude scaling?

This is conducted by using experimental data and numerical data from FDS simulations, and further comparing this to the resulting radiation that Froude scaling would give.

2 THEORETICAL BACKGROUND

2.1 MODES OF HEAT TRANSFER

There are two modes of heat transfer. It happens through either conduction or radiation.

- Conduction is when molecules react and transport energy
- Radiation is the transport of electromagnetic energy that is emitted from a body possessing thermal energy. [2]

2.1.1 Conduction

Is expressed by Fourier's Law:

$$\dot{q}'' = -k\nabla T$$

Where:

$\dot{q}''$ is the heat flux-energy flow rate per unit area [W/m^2]

k is the thermal conductivity of the system [W/m·K]

∇T is the temperature gradient of the system [K]

2.1.2 Thermal radiation

Was defined in the 1900s by Planck's Law, which gives the ideal energy emitted per unit area [2].

$$E_{b,\lambda} = \frac{C_1 \lambda^{-5}}{e^{\frac{C_2}{\lambda T}} - 1}$$

Where:

$E_{b,\lambda}$ is the emitted energy and wavelength

$C_1 = 3.743 \cdot 10^8 \, [\frac{W \mu m^4}{m^2}]$

$C_2 = 1.4387 \cdot 10^4 [\mu m \cdot K]$

T is the temperature of the body [K]

λ is the wavelength of the energy $[\mu m]$

Considering every wavelength of the spectrum and accounting for all energy in a system the blackbody equation can be derived:

$$E_b = \sigma T^4$$

Where:

σ is Stefan-Boltzmanns constant, $5.67 \cdot 10^{-8} \, [\frac{W}{m^2 K^4}]$

A black body is a surface/material that absorbs all the energy transmitted from sources, making it a perfect absorber [2].

2.2 Radiation

Radiation can be absorbed (α), reflected(ρ), or transmitted(τ) through matter. Almost no surfaces can be considered as black bodies. The property that determines the absorptivity, reflectivity and transmission is called emissivity, ϵ. This depends on the temperature and medium, and further the wavelength of incident thermal radiation [2].

The emissive power is given as:

$$E = \epsilon E_b = \epsilon \sigma T^4$$

Kirchhoff's Law states that the emissivity and absorptivity are equal for bodies of the same temperatures [2]:

$$\alpha_\lambda = (\lambda, T) = \epsilon_\lambda(\lambda, T)$$

This is only valid for bodies of the same temperatures, however due to the complexities of radiative heat transfer the assumption

$$\alpha(T) = \epsilon(T)$$

Is useful. This is called the grey body assumption

2.3 Froude number

Froude number is a dimensionless quantity used to describe the effect gravity has on fluid motion. Often expressed as:

$$Fr = \frac{v}{(gd)^{\frac{1}{2}}}$$

Where:

v is the rapidity of motion of a small surface wave

d is the depth of flow

g is the gravitational constant

In general:

- If $Fr < 1$ small surface waves can move upstream
- If $Fr > 1$ surface waves will be carried downstream
- If $Fr = 1$ the velocity of the flow is equal to the velocity of surface waves. [3]

2.3.1 Froude modeling

In order to perform Froude modeling the Froude number must be preserved. By setting the Froude number equals to 1 for natural convection, the Froude number is preserved. The solid boundary effect must be neglected in order to ignore the Reynolds number. It is not possible to preserve all of the radiation and conduction when doing Froude modeling.

Setting the Froude number to 1 leads to the following relations:

$$Fr = \frac{v}{\sqrt{gd}} = 1(EQ8)$$

This must be true for all model-scales, which leads to:

$$Fr_M = Fr_F$$

Where:

M is model scale

F is the reference scale

$$\frac{v_M}{\sqrt{gd_M}} = \frac{v_F}{\sqrt{gd_F}} \rightarrow v_F = v_M\sqrt{\frac{d_F}{d_M}} = v_M\sqrt{\lambda}$$

Where:

λ is the geometrical relation between model and reference scale.

The following relations can be discerned from equation 8:

Table 1 Froude-scaling relations

Type of unit	**Scaling**
Effect [kW]	$\frac{Q_M}{Q_F} = \left(\frac{L_M}{L_F}\right)^{\frac{5}{2}}$
Velocity [m/s]	$\frac{V_M}{V_F} = \left(\frac{L_M}{L_F}\right)^{\frac{1}{2}}$
Time [s]	$\frac{t_M}{t_F} = \left(\frac{L_M}{L_F}\right)^{\frac{1}{2}}$
Energy [k]	$\frac{E_M}{E_F} = \left(\frac{L_M}{L_F}\right)^{3}$
Mass [kg]	$\frac{m_M}{m_F} = \left(\frac{L_M}{L_F}\right)^{3}$
Temperature [K]	$\frac{T_F}{T_M} = 1$
Distance [m]	$\frac{x_F}{x_M} = 1$

2.4 Scaling Heat Transfer

The information in this subsection is gathered from Tunnel Fire Dynamics (2015) by Haukar Ingasson, Ying Zhen Li and Anders Lônnermark.

Convective heat transfer is has properties that makes it scalable if the flow is turbulent and the relative roughness of the flow remains constant. The convective heat transfer scales as:

$$h_c \propto l^{\frac{1}{2}}$$

The radiative heat transfer there are several factors that need to be considered, as this depends upon the geometry, view-factor, soot. Therefore it is simplified as:

$$\dot{Q}_r = h_r A_w (T_g - T_w)$$

Where:

h_r is the radiative heat transfer coefficient

The radiative heat transfer coefficient is defined as:

$$h_r = \epsilon\sigma(T_g^2 + T_w^2)(T_g + T_w)$$

2.5 Computational Fluid Dynamics (CFD)

The following information is gathered from Computational Fluid Dynamics: Principles and Applications, J. Blazek.

In the 70s, CFD became the name for the use of numerical calculations and physics in computer science. Following an advancement in the complexity and processing power of computers, simulations could be performed with greater accuracy. Using the governing equations, it became possible to simulate fluid mechanics scenarios with greater link to real life scenarios, such as fires. The equations are solved over grid cells, and each grid cell can be considered its own environment.

2.5.1 Governing equations

The governing equations consists of the conservation of mass, momentum and energy. The following equations are used:

The general form of the equation (21) the conservation of mass, states that the mass only changes, it does not deteriorate nor is it created.

$$\frac{\partial \rho}{\partial t} + \nabla\, \rho u = 0$$

For conservation of momentum, the force on the material equals the momentum on the material. Described with:

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho u u) = -\nabla \mathrm{p} + \mathrm{f} + \nabla \tau$$

The conservation of energy uses source terms to incorporate combustion, HRR, conduction, radiation, pressure and kinetic energy.

$$\frac{\partial(\rho h)}{\partial t} + \nabla(\rho h u) = \frac{Dp}{Dt} + \dot{q}''' - \nabla \cdot \mathrm{q} + \varepsilon$$

2.5.2 Turbulence modelling

Fluid flows is divided into two main categories, turbulent and laminar flow. A laminar flow is considered a stable flow, and a turbulent flow is considered unstable. A laminar flow is more easily solved as opposed to the more unstable turbulent flow.

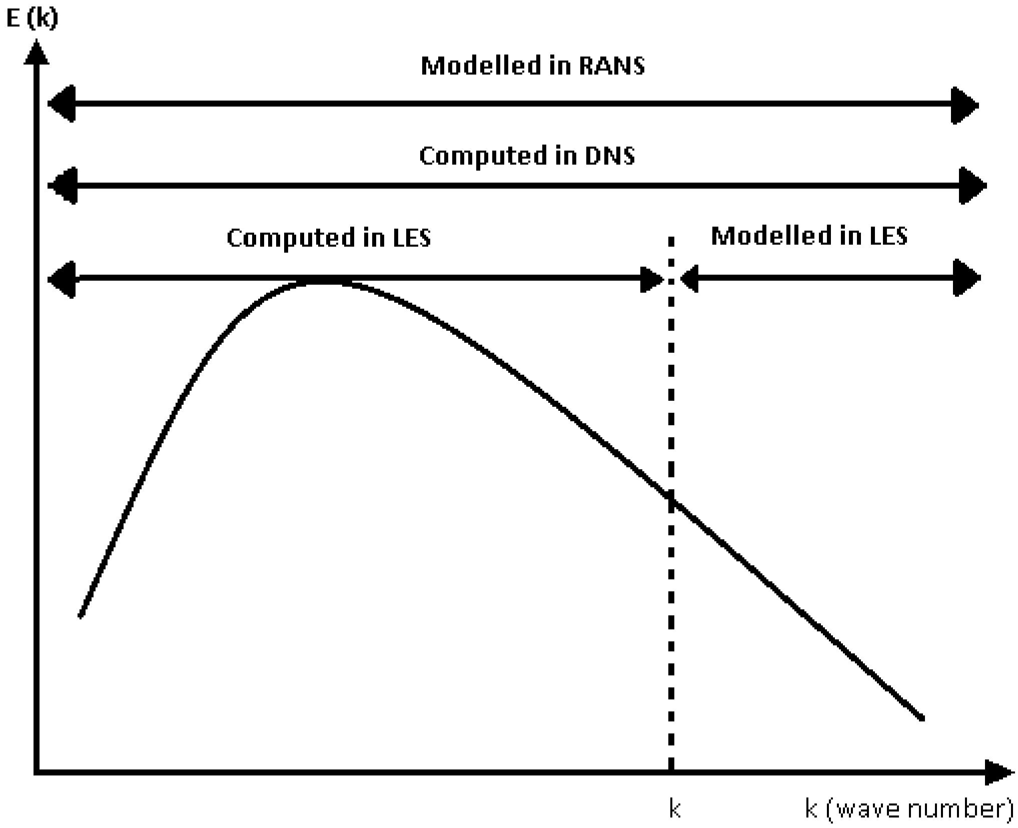

Figure 1 Turbulence modelling

There are 3 main ways of modelling turbulence, Reynolds average Navier-stokes(RANS), Large Eddy Simulation(LES) and direct numerical simulation. [4]

The way used in this thesis is LES, which calculates the larger turbulent structures and averages (simulates) the smaller turbulent structures. [4]

3 METHODS

3.1 EXPERIMENTAL SETUP

The purpose of the experiments was to examine if Froude-scaling properties were maintained for radiation for different scale-models. Table 2 show the different scale models tested.

Table 2 Scale models

Model	Scale (%)	Effect (kW)	Burner size (cm)	Burner distance (m)
1	100	100	30 x 30	0.5
2	66.67	36.29	20 x 20	0.33
3	50	17.68	15 x 15	0.25
4	33.34	6.42	10 x 10	0.17

A water-cooled heat flux meter measured the radiation from a flame originating from a mass flow controlled propane burner. Illustrated in figure 2.

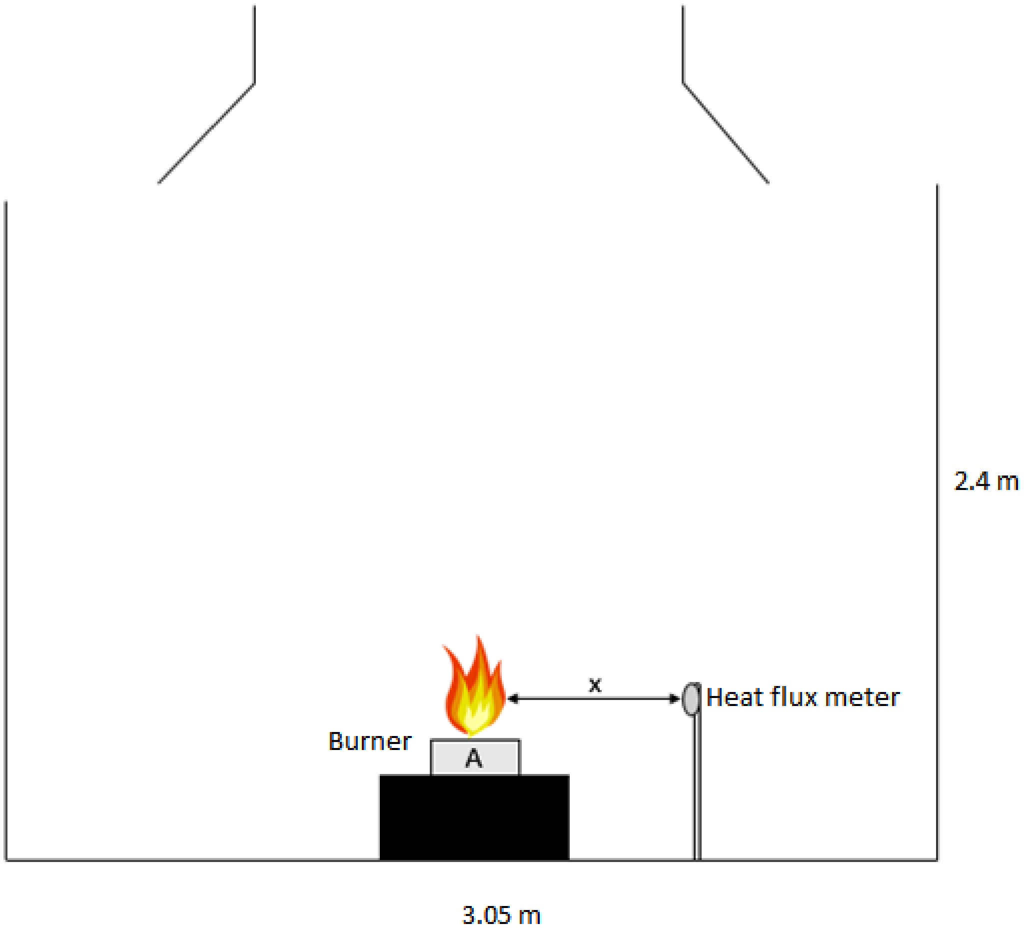

Figure 2 Experimental setup

3.1.1 Model scaling

Model 1 was used as reference scale from which the other models were scaled. The burner size of model 1 became the reference length for the entire experiment.

3.1.2 Radiative heat flux measurement

The radiative heat flux was measured using a heat flux meter. The reference distance between the heat flux meter and burner was chosen based upon the rated measurement range of the heat flux meter of 5 kW/m^2. [5] The heat flux meter was facing approximately at the centerline of the plume.

3.1.3 Heat release rate

A mass-flow controller (Brooks SLA 5832 S) determined the effect of the flame ranging from 0 to 225 l/m, the fuel used was propane (C3H8).

3.1.4 Burners

The experiments were conducted using four sandbox burners of different sizes. The dimensions of the burners are listed in table 2. The burners were elevated approximately one meter, but this was determined to have little to no effect on the experiments.

3.2 Setup of Fire Dynamics Simulator (FDS) simulations

3.2.1 General

The FDS simulations were setup in as similar manner as possible as the experimental setup was conducted. The heatflux was measured in a different manner using a Lagrangian particle as a surrogate for the heat flux meter.

Using the following line of code, this was possible:

```
&DEVC ID='flux', QUANTITY='RADIATIVE HEAT FLUX GAS', XYZ=0.45,0.0,0.3,
ORIENTATION=-1,0,0 /
```

3.2.2 Fuel source

The fuel used in the simulations was propane (C3H8) with the following properties:

- Soot yield of 1%
- Heat of combustion: 46460 kJ/g

And the following Heat Release Rate Per Unit Area (HRRPUA):

Table 3 HRRPUA for each burner size

Burner size [cm]	**0.3 cm**	**0.2 cm**	**0.15 cm**	**0.1 cm**
HRRPUA [kW/m^2]	1111	403	196	71

3.2.3 Scaling

The simulations were scaled according to table 2, concerning the burner and geometry of the burner. The room size had to stay the same, as this was not possible to change in the experiment.

3.2.4 Grid sensitivity analysis

In order to insure accuracy in the data following a simulation, a grid sensitivity analysis has to be executed. There are several ways of doing this.

For simulations involving a buoyant plume, a non-dimensional expression, D*/dx can be used, where dx is the cell size and D* is a dimensionless diameter expressed as followed:

$$D^* = \left(\frac{\dot{Q}}{\rho c_p T \sqrt{g}}\right)^{\frac{2}{5}}$$

A ratio of D*/dx between 4 and 16 is recognized as sufficient, but in order to conclude a converged solution a grid sensitivity analysis has to be performed.

4 RESULTS

4.1 EXPERIMENTAL

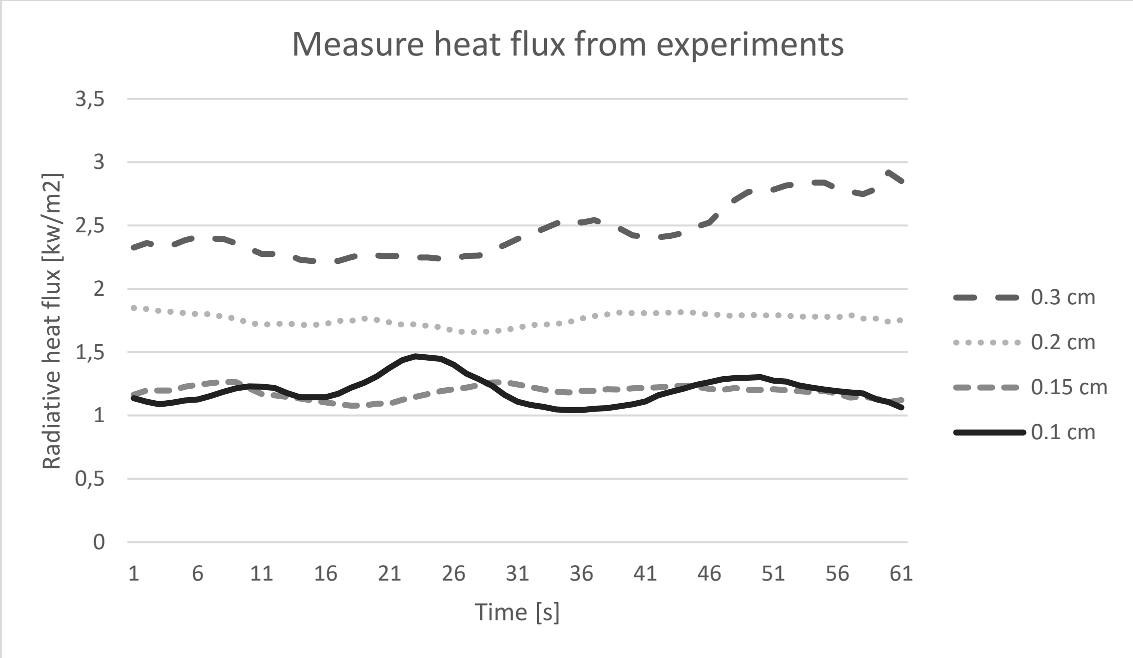

Figure 3 Measured heat flux from experiments

A steady decline in the heat flux as the HRR decreased was expected. As the HRR got smaller the resulting heat flux did not differ too, this may be an uncertainty in the measuring device. As the heat flux meter is meant for heat fluxes > 5 kw/m^2.

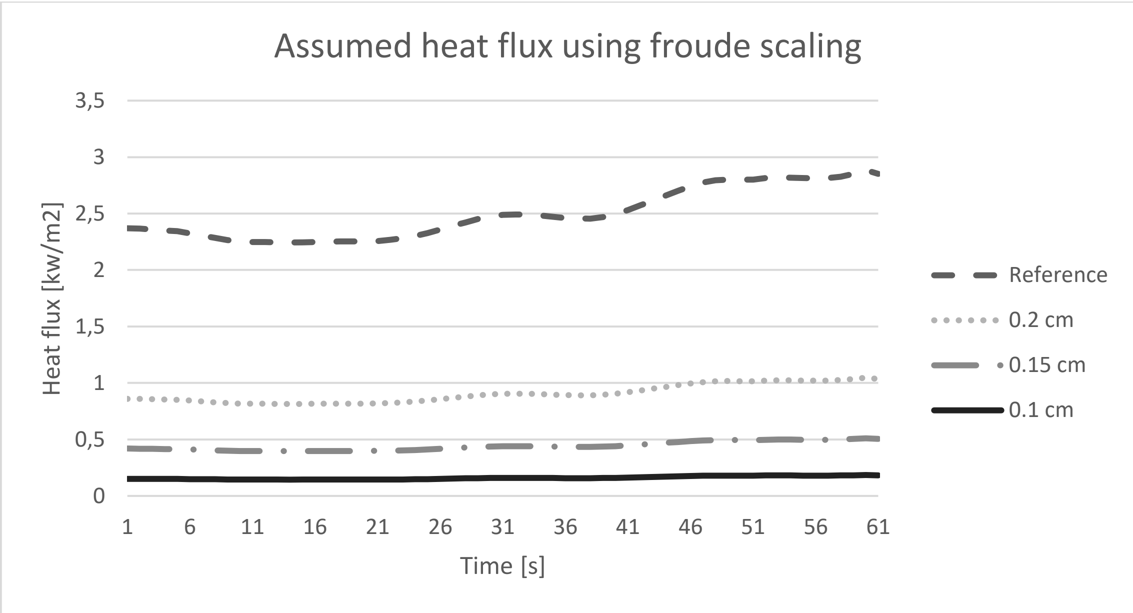

Figure 4 Assumed heat flux using froude scaling

Using 0.3 cm burner as a reference, and scaling down the results from that experiment using Froude scaling shows an increasing underestimation of the radiation compared to the experimental data.

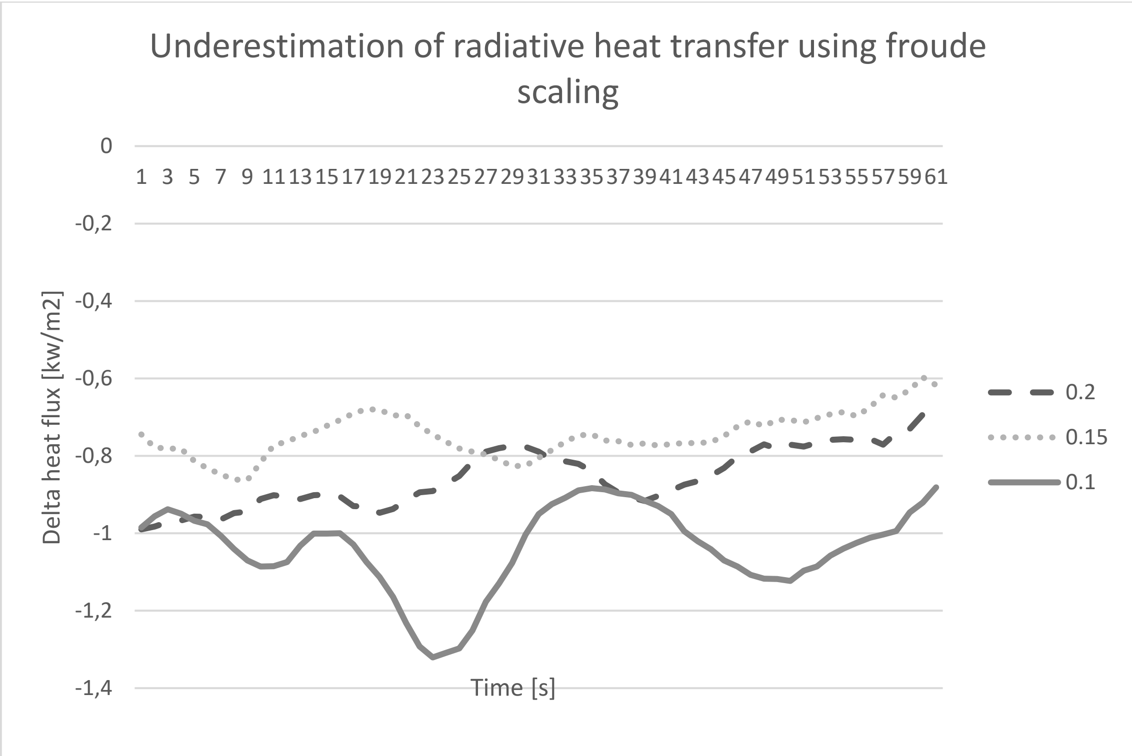

Figure 5 Underestimation of heat flux using froude scaling

Table 4 Percent of underestimation occurring using froude scaling

0.2 cm	**0.15 cm**	**0.1 cm**
49%	63%	87%

Figure 4 and table 3 shows the amount of underestimation that is occurring using Froude scaling.

4.2 FDS

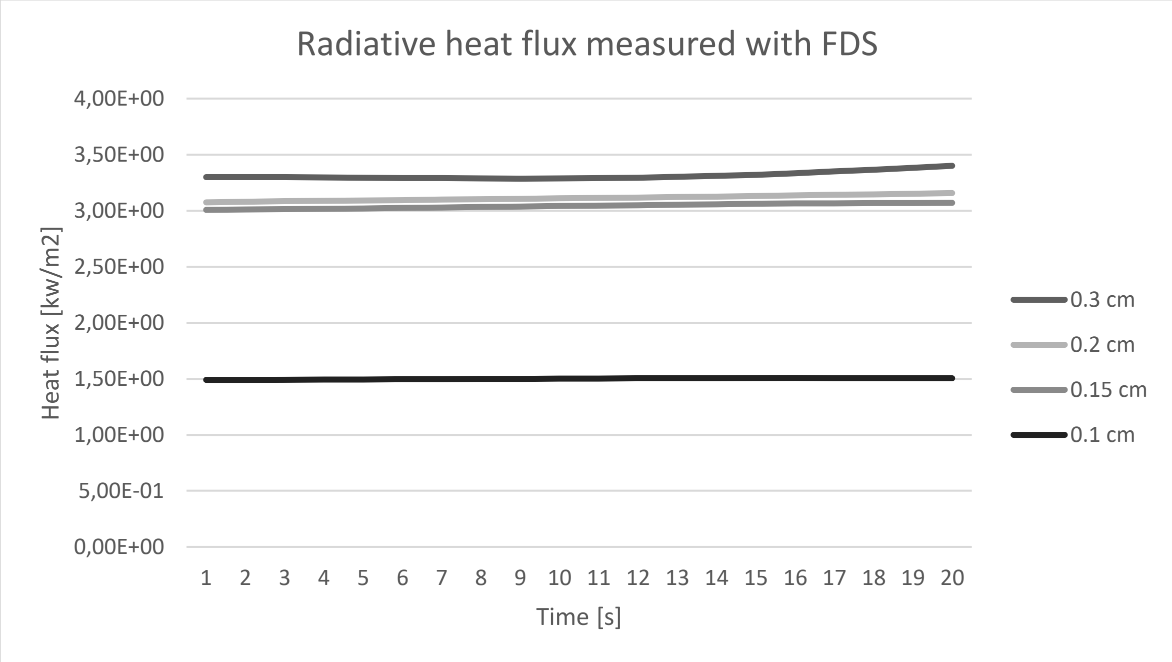

Figure 6 Radiative heat flux measured with FDS

There is some discrepancy when comparing the experimental data with the FDS simulations. The heat flux does not differ too much with decreasing burner sizes and HRR. This is most likely because in the FDS simulations the environment was perfect; there was no wind, pressure differences or other external forces affecting the fire.

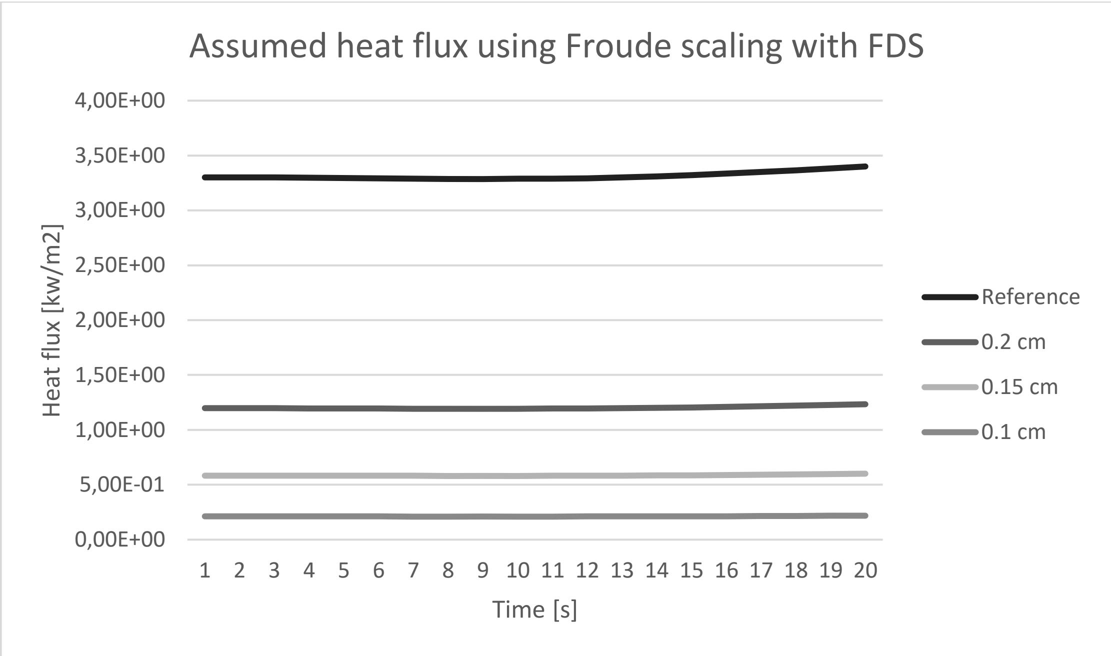

Figure 7 Assumed heat flux using Froude scaling with FDS

Considering the assumed heat flux that is calculated using Froude scaling, the same underestimation of the heat flux is occurring, but on an even larger scale. The heat flux is being calculated using Froude scaling, with 0.3 cm burner as a reference point.

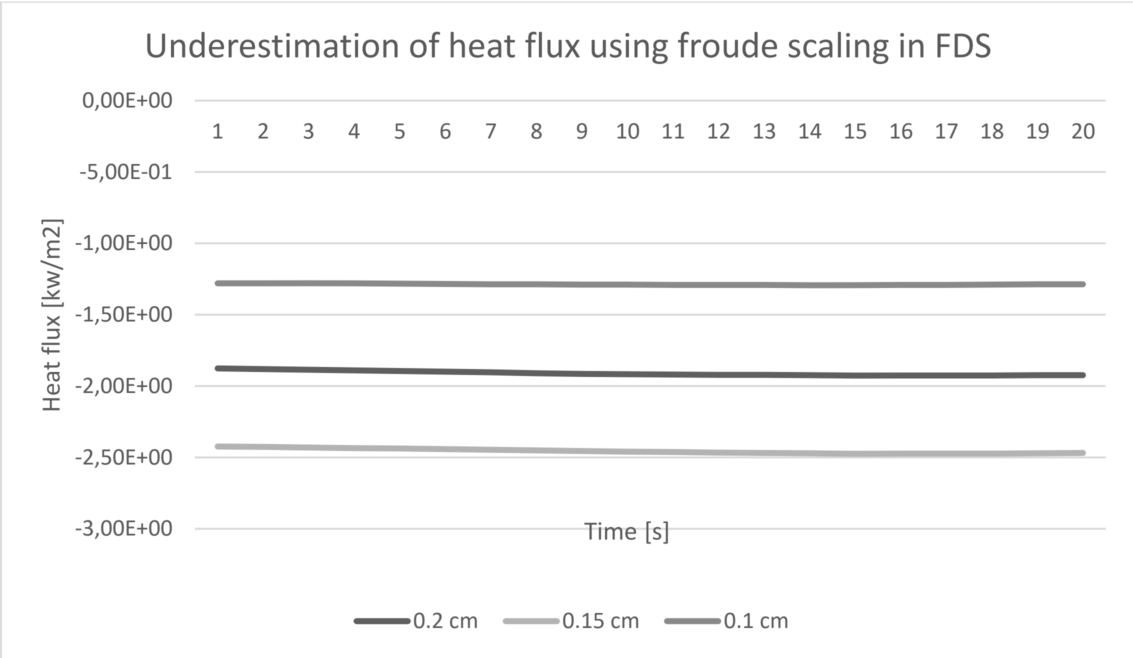

Figure 8 Underestimation of heat flux using froude scaling in FDS

Table 5 Percentage of underestimation occurring using froude scaling

0.2 cm	0.15 cm	0.1 cm
61%	81%	86%

The same trend as seen in the experimental results can be seen in the numerical results in figure 8 and table 4; the further down the fire is scaled the more severe the radiation is underestimated.

4.3 RESULTS OVERALL

The results seem to confirm that Froude scaling is underestimating the radiative heat transfer. An error of 49% all the way to 87% the more the model is downscaled. From this, it seems that scaling down to 2/3 of the model-size has an error of 49%. While scaling down to 1/3 results in an error of 87%.

5 CONCLUSION

Given the area of research that downscaling is being used on, it seems that the underestimation can have significant impact on the results. The results in this study implies that the further something is downscaled the greater the impact it has on the underestimation of the radiative heat transfer. Special care should be taken when considering a model that has been scaled down significantly.

From these results, it would be recommended to consider this underestimation, especially in regards to fire safety. An error between 49 – 87% can have high risk attributed to it. As this affects all aspects of the scenario being downscaled, from the incident radiative heat, to the total HRR from the fire-source itself.

6 FURTHER WORK

For further work, it is suggested to study how big the impact of downscaling has on the underestimation of the results. A more accurate assessment of this will lead to better scale models, and can provide a safety margin when considering fire safety questions. The underestimation may follow some sort of pattern, and if this pattern can be discerned, the effect may be counteracted by adjusting the HRR or some other factor in the simulations/experiments.

7 BIBLIOGRAPHY

[1] J. Q, "Scaling applications in Fire Research," Fire Safety Journal, 1989.

[2] B. Karlsson and J. G. Quintiere, Enclosure Fire Dynamics, United States: CRC Press LLC, 1999.

[3] Encyclopedia Britannica, Froude-Number, The editors of Encyclopedia Britannica, 1998.

[4] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd , C. Winschenk and K. Overholt, "Fire Dynamics Simulator Technical Reference Guide Volume 1: Mathematical Model," NIST, National Institute of Standards and Technology, 2013.

[5] Hukseflux, "Hukseflux," [Online]. Available: https://www.hukseflux.com/sites/default/files/product_manual/SBG01_manual_v1722.pdf. [Accessed 4 November 2017].