UNIVERSITY OF TURKU

Reference standard for heat flux by conduction

Department of Mechanical and Materials Engineering

Bachelor's thesis

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ABSTRACT

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The purpose of this thesis is to note the lack of reference standards for heat flux and introduce the need of a new national reference standard for heat flux with presenting a few solutions to that possible reference standard by conduction. Since heat flux by conduction is the most important way of heat transfer in building and machine industry, the thesis is focused on conduction. The thesis is conducted with a literature review collecting information from articles and different standard organizations.

Currently there is lack of reference standards for heat flux that can lead to insufficient results in terms of traceability and comparability. The reasons might be related to the heat dissipation and changes in heat transformation methods, but the thesis presents couple setups that could be used in the standardization of a heat flux by conduction.

Key words: Heat flux, Reference standard, Heat flux meter, Heat-flow density

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Tämän tutkielman tarkoituksena on huomioida lämpövuon mittanormaalien puute ja tuoda esiin tarve uudelle kansainväliselle lämpövuon mittanormaalistandardille. Uudelle standardille esitetään myös toteutustapoja sille, miten saataisiin vertailustandardi johtumalla esiintyvälle lämpövuolle. Koska lämpövuo on tärkein lämmön siirtymisen tapa rakennus- ja koneteollisuudessa, tämä tutkielma keskittyy pääasiassa lämmön johtumiseen. Tutkielma on toteutettu kirjallisuuskatsauksena, jossa kerätään tietoa artikkeleista ja eri standardiorganisaatioilta.

Tällä hetkellä lämpövuon mittanormaaleiden puute voi johtaa riittämättömiin tuloksiin jäljitettävyyden ja vertailukelpoisuuden suhteen. Syyt tähän voivat liittyä lämpöhäviöihin ja vaihteluihin lämmön kulkeutumistavoissa. Tutkielma esittää muutamia eri tapoja, joilla yhdensuuntainen lämpövuo johtumalla voidaan saada aikaan.

Avainsanat: Lämpövuo, Vertailustandardi, Lämpövuomittari, Mittanormaali

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1 Introduction

The purpose of this thesis is to point out the nonexistence of proper reference standards for heat flux and bring up the need for an international reference standard for heat flux. Currently there is a lack of suitable reference standards that could be used in calibration, even though there are many available international standards focusing on the measurement techniques of heat flux meters [1]. Heat flux is utilized in many applications involving heat transfer, like estimating the thermal efficiency of a house or controlling an industrial process furnaces. Because conduction plays such a big role in those examples, the focus on this thesis is mainly concerned on the conduction and how to create a reference standard to that. The thesis is conducted with a literature review, collecting information from articles and different standard organizations.

To gain an understanding of measuring heat flux and its applications, they are briefly explained in chapter 2. In chapter 3, standards and their importance are presented with an example of international temperature standard that goes hand to hand with the possible reference standard for heat flux. After that the Guarded Hot Plate apparatus is explained and a couple of calibration methods for heat flux meters is presented in chapter 4 that could be used to generate the reference standard by conduction. Finally, the results are summarized and discussion about the results and problems concerning those are done in the chapter 5.

2 Heat Flux

Heat flux is a vector quantity that expresses the amount of energy transfer per unit area perpendicular to the energy flow like it can be seen in Figure 1. It is expressed with a symbol q'' with q and A being the heat rate and area, respectively. Heat flux and heat transfer happens only when there is temperature difference between inspected points. Heat energy cannot be measured in one point.

$$q''[\frac{\mathrm{W}}{\mathrm{m}^2}] = \frac{q}{A} \quad (1)$$

Heat flux can also be referred as Thermal flux or Heat flow density but in this thesis the term Heat flux is used. This thesis mainly focuses on the one-dimensional heat fluxes by conduction. [2]

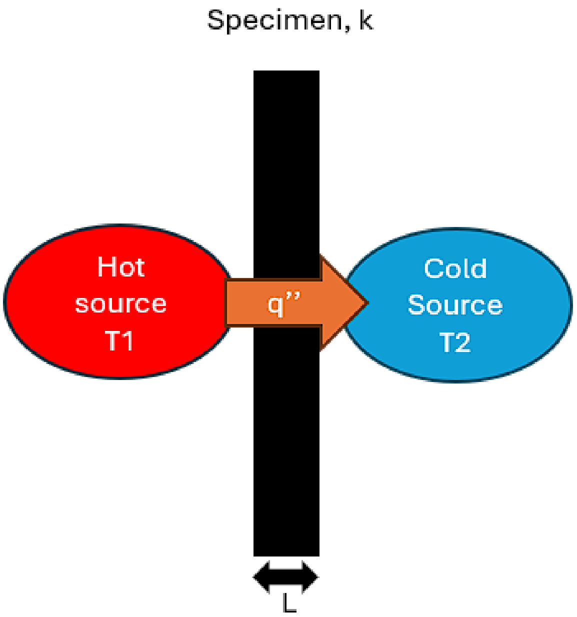

Figure 1 Heat flux by conduction

2.1 Heat flux usage

Because heat flux determines how much heat energy flows through some area, it is a good way to determine for example the efficiency of the heat insulation of a building and with that the heat loss of the building will be known to save energy. In any kind of furnace or radiator, heat flux is needed so energy balance in a house can be adjusted. In industrial process furnaces the heat flux is used to control the furnace to save energy and cost. Heat flux is also important when studying the appearance of wildfires and making proper firefighting gear. In conclusion, the heat flux is needed in almost all of the applications that include heat transfer [3–6]

2.2 Measuring heat flux

Heat can transfer in three different ways that are conduction, radiation, and convection. In all these cases there will also be a heat flux. If more than one heat transfer form exists in a system, the total heat flux will be the sum of the existing forms of heat fluxes. Direction of the heat flux will always be from the hot temperature to the cold temperature. Since there are no devices that can measure energy and heat flux directly, a different method for analysing heat flux is needed. These methods usually consist of measuring the temperature difference. [7]

2.2.1 Conduction

In conduction, the one-dimensional heat flux in steady state is calculated with phenomenological law called the Fourier law of heat conduction.

$$q'' = k * \left(\frac{\Delta T}{L}\right) \qquad (2)$$

Where $k[\frac{W}{(m*K)}]$ is the materials thermal conductivity and L is the thickness. As seen or as it can be seen, the temperature difference is needed to calculate the heat flux by conduction. [2,8]

2.2.2 Radiation

In radiation from a solid grey surface, the net heat flux is calculated as follows.

$$q'' = \varepsilon * \sigma * (T_s^4 - T_\infty^4) \qquad (3)$$

Where ε is the emissivity of the solid matter from 0 to 1, is the σ is Stefan Boltzmann constant, T_s the temperature of the surface and T_∞ the temperature of the surroundings. So the temperature is again needed to calculate the heat flux. [2]

2.2.3 Convection

Heat can transfer in two different ways in convection; forced convection and natural convection. In natural convection the moving of the fluid is induced by the buoyancy forces that come from the density differences caused by the temperature changes. In forced convection the moving of the fluid is caused by external force such as a fan. Both convection ways are still calculated with the Newtons law of cooling.

$$q'' = h * (T_s - T_\infty) \tag{4}$$

Where $h[\frac{W}{(m^2 * K)}]$ is the convection heat transfer coefficient that depends on the boundary layer conditions. The coefficient values can be estimated with different equations but is difficult to estimate the right value. [2,8]

2.3 Example of heat flux meter

When measuring a steady state conduction heat flux in one dimension with a heat flux sensor, the thermopile heat flux gauge is commonly used. The method for measuring the heat flux with the meter is to put the meter flat on the wall so that the other side is touching the wall with wall temperature and other side is in the surrounding temperature. Thermopile gauges do not need any outside energy source since the temperature difference in the thermocouples creates the voltage output. Thermopile gauges, that can be seen in Figure 2, consist of two layers of interconnected thermocouples that are connected in series and protected by protective layers on the outside surfaces. The layers are very thin and between those layers, there is a thin insulation layer with known thermal conductivity and thickness. [1,9]

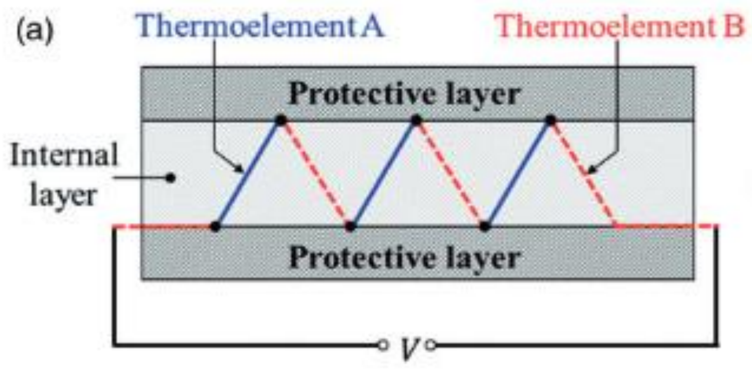

Figure 2 Schematic of a typical thermopile heat flux gauge [9]

The principle of thermocouples is based on the Seebeck effect where two different metal wires create a voltage when there is a temperature difference in the ends of the wires. In thermopile gauges, the thermocouples are connected so that they measure the temperature difference between the insulation layers. The thermocouples are usually T-type, and the thermopiles can consist of 54 thermocouples. The temperature difference can be achieved form the voltage with a following formula, where S_t is the sensitivity of one thermocouple and n is number of thermocouples in series. [9]

$$\Delta T = \frac{V}{S_t * n} \tag{5}$$

Now when the temperature difference is achieved, all values for Fourier law of heat conduction (equation 2) are known. Next equation is used to calculate the sensitivity of the Heat flux gauge. In equation 6, the Fourier law is inputted in q and equation 5 to the V. [9]

$$S = \frac{V}{q''} = \frac{L * n * S_t}{k} \tag{6}$$

The voltage can now be linked to the heat flux with the sensitivity. It can be seen from the equation 6 that the sensitivity is higher with more thermocouples connected. Also, small thermal conductivity and thick insulation layer will increase the sensitivity. The downside of increased sensitivity is that the thermal field of measured object will have distortion due to the gauge. [9]

Other meters have also been invented to detect radiation and radiative-convective heat flux. Gauges like Schmidt-Boelter, Gardon, DFT and HFG are used in these conditions. The main working principle of all of these gauges is to have a surface that has close to a blackbody absorptivity. For example, Schmidt-Boelter has 0.94. Next to the absorbing surface there is insulation and sensor plate that can be water cooled. Between those sides is thermocouple the same way with thermopile heat flux gauge. So the radiation heat flux gauges turn the radiation into conduction and then measure that. [5]

2.4 Example of HFM in application

One example of where these kinds of Thermopile heat flux meters (HFM) are used is when determining the thermal resistance of a building wall, so that for example, energy efficiency calculations can be made. The thermal resistance is referred as $R\ value \left[\frac{m^2*K}{W}\right]$ in the construction industry. The most common and only standardized method of estimating the R value is the method with heat flow meter, ISO 9869-1. [10]

$$R = \sum_{j=1}^{n} T_{si,j} - T_{se,j}\ / \sum_{j=1}^{n} q''_{si,j} \tag{7}$$

With Equation 7, the R value can be estimated with average method in long time period, where n is the number of measurement data and $T_{si,j}$, $T_{se,j}$ are internal and external temperatures of the wall surface, respectively. The equation could be also used without sums if the conditions were steady-state but because that is not the case in construction sites, long tests of three days need to be made to achieve steady-state R value estimation. Like it can be seen in Figure 3, the Heat Flux Meter is often placed in the inside wall surface. That is because the air inside is usually more stable and the temperature often remains constant. [10]

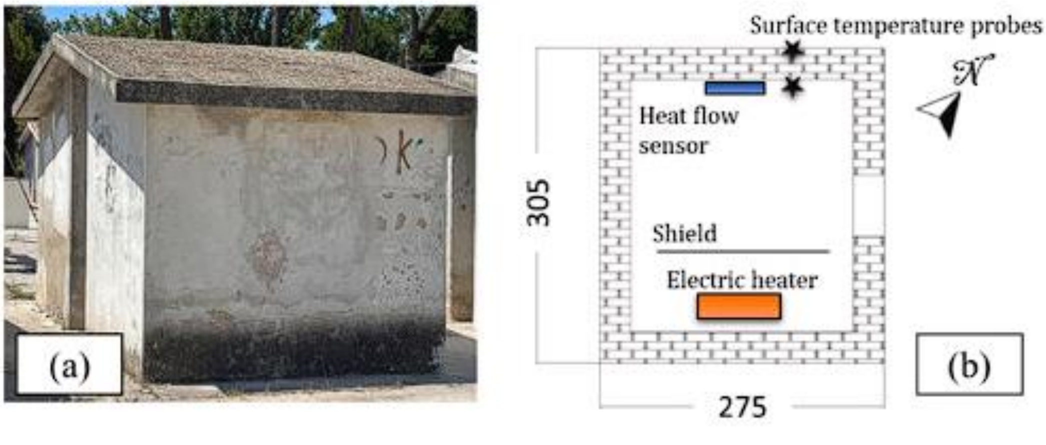

Figure 3 Heat flux sensor inside of the building and thermocouples measuring wall temperatures in both sides. [11]

3 Standards and ITS-90

This chapter describes why different standards and reference standards are important in metrology and science. Also, one wildly used reference standard example is given with temperature that goes hand in hand with heat flux and heat transfer.

3.1 Standards

Standards are created documents or references from different standard organizations that sets a way of doing certain things in certain way. The idea of standards is to make an agreed way of doing something. [12] For example many screws used nowadays in the world are done according to the ISO 262:2023- standard that sets a standardized size and threads for screws, like M8 bolt [13]. The screws are not the only thing standards are used. Standards help people and corporations to do the things consistently no matter where they come from. Standards are done by many different organizations like ISO, ASTM or BIPM and some of the organizations can be international, meaning that many countries use the same standards, like ISO. Also, some standards are regional, like European Union’s EN standards and some are national like SFS (Suomen Standardisoimisliitto ry) in Finland. [14]

Standards cover many categories including environment, construction, energy and more. Those categories are covered by different organizations and most of the time, more than one organization. [14] For example ISO covers environmental standards to IT security standards to many more. IEEE SA (Institute of Electrical and Electronics Engineers Standards Association) on the other hand concentrates on technology and electronic standards. [12,13]

3.1.1 Reference standards

In the technology and science area of standards there are two major types of standards that are documentary standards and measurement or reference standards. Documentary standards are documents that present an agreed way of doing a technical process, like calibration of an equipment or doing a measurement of the thermal resistance of a wall (ISO 9869-1). The documentary standards are usually done by experts in the matter and then recognized by a professional organization, like ISO. [15]

Figure 4 A reference standard for one kilogram from 1875 to 2018 [15]

Reference standard or measurement standard is the standard needed for heat flux. Reference standards produce quantities such as meter, kilogram, or temperature. Reference standards can be physical objects like the old kilogram reference standard seen in Figure 4 or they can be produced with other unit for example meter is defined as the distance light travels in $1/299.792.458$ of a second in vacuum. Reference standards that can be produced in the laboratory without the need of the same unit are called primary standards but there is always a calculated uncertainty. For example, a one-meter stick calibrated with the primary standard of meter, is a secondary reference standard and uncertainty. The main purpose for reference standards is to help calibrate secondary standards and different meters. [15,16]

One of the biggest international reference standard organizations in the world is BIPM (Bureau International des Poids et Mesures). It was established in the Metre Convention in 1875. BIPMs main function is to maintain the International System of Units (SI) and the international reference time scale (UTC). Under BIPM there are also CIPM and CGPM that are the international committee and general conference on weights and measures. [17,18]

3.2 ITS-90 Reference Standard

When the heat flux has only a few available reference standards, temperature has one that covers the temperature range from $0.65\ K$ to the highest temperature possible to measure in terms with the Planck radiation law. In 1989 the International Temperature Scale called ITS-90 was created by the International Committee of Weights and Measures (CIPM) to better cover the temperature range than the former International Practical Temperature scale and many more. The scale uses Kelvin $[K]$ as a unit of temperature but because Celsius $[°C]$ uses the same scale both can be used, and the ITS-90 provides the scales for both. Kelvin is defined with the triple point of water and it is a fraction $\frac{1}{273.16}$ of that thermodynamic temperature and the Celsius is defined with the difference from the freezing point $273.15\ K$ [1,19]

The ITS-90 consists of several ranges and sub-ranges of temperatures that cover the whole temperature range. Some of the ranges and sub-ranges can have overlap so the same temperature has two or more definitions but the real changes in the temperature are very minor and still are consistent with the scale. It is then acceptable to use either one of the overlapping temperature references. The [19]

The Temperature ranges can be defined with $^{3}He\ and\ ^{4}He$ vapor-pressure temperature relations in the lowest range from $0.65\ K$ to $5.0\ K$. The range from $13.8033\ K$ to $961.78\ °C$ is defined from The Triple Point of Equilibrium Hydrogen to the freezing point of Silver and that is done with a Platinum Resistance Thermometer (PRT). Because the range is so wide, there can not be any single PRT that can measure the whole range accurately. That is why sub-ranges are specified to interpolate between smaller fixed ranges and also different ranges must be measured with different PRT characteristic which are listed in Supplementary information list in ITS-90. [19]

The equations 12 is example of the reference function that is used to define the PRT calibration range described in the paragraph above.

$$W(T_{90}) = R(T_{90})/R(273.16\ K) \tag{12}$$

Where W is the ratio between the PRT resistance in the measured temperature $R(T_{90})$ and resistance at the triple point of water.

$$\ln[W(T_{90})] = A_0 + \sum_{i=1}^{12} A_i \left[\frac{\ln\left(\frac{T_{90}}{273,16}K\right)+1,5}{1,5}\right] \tag{13}$$

Where A_0 to A_i are constants for the reference function that can be found in the table from ITS-90. There are also similar reference functions for the temperature differences above the freezing point and other definitions with different ranges, like from $0\ °C$ to the freezing point of Zinc $(419{,}527\ °C)$. The fixed points of the temperature scale can be seen in the Table from the Figure 5, where “state” means the state in which the temperature is on the specific matter.

V, T, G, M and F mean Vapor pressure point, Triple point, Gas thermometer point, Melting and Freezing point, respectively. [19]

Number	Temperature		Substance[a]	State[b]	$W_r(T_{90})$
	T_{90}/K	t_{90}/°C			
1	3 to 5	−270,15 to −268,15	He	V	
2	13,8033	−259,3467	e-H_2	T	0,001 190 07
3	≈17	≈ −256,15	e-H_2 (or He)	V (or G)	
4	≈20,3	≈ −252,85	e-H_2 (or He)	V (or G)	
5	24,5561	−248,5939	Ne	T	0,008 449 74
6	54,3584	−218,7916	O_2	T	0,091 718 04
7	83,8058	−189,3442	Ar	T	0,215 859 75
8	234,3156	−38,8344	Hg	T	0,844 142 11
9	273,16	0,01	H_2O	T	1,000 000 00
10	302,9146	29,7646	Ga	M	1,118 138 89
11	429,7485	156,5985	In	F	1,609 801 85
12	505,078	231,928	Sn	F	1,892 797 68
13	692,677	419,527	Zn	F	2,568 917 30
14	933,473	660,323	Al	F	3,376 008 60
15	1234,93	961,78	Ag	F	4,286 420 53
16	1337,33	1064,18	Au	F	
17	1357,77	1084,62	Cu	F	

Figure 5 Table for different temperature ranges. [19]

3.3 Calibration and traceability

The main usage of reference standards is in calibration of equipment [15]. In calibration, the measuring device being calibrated is set according to the reference standard that can be found in national metrology institutes. [1], [9] The reason for calibration is to reduce the difference between the readings on the measurement device and the reference point. [20] Like reference standards, calibrations and therefore measurement devices have an uncertainty and the uncertainty increases in every calibration procedure from SI- units to the final device [21].

Because the uncertainty increases in every step going down on the pyramid in Figure 6, it means that every uncertainty needs to be known. Therefore, so that the result of the device can be compared with other results, the path from SI units to the device needs to be documented. When the calibration chain of the measurement is traceable it can be compared with other measurements. [21,22]

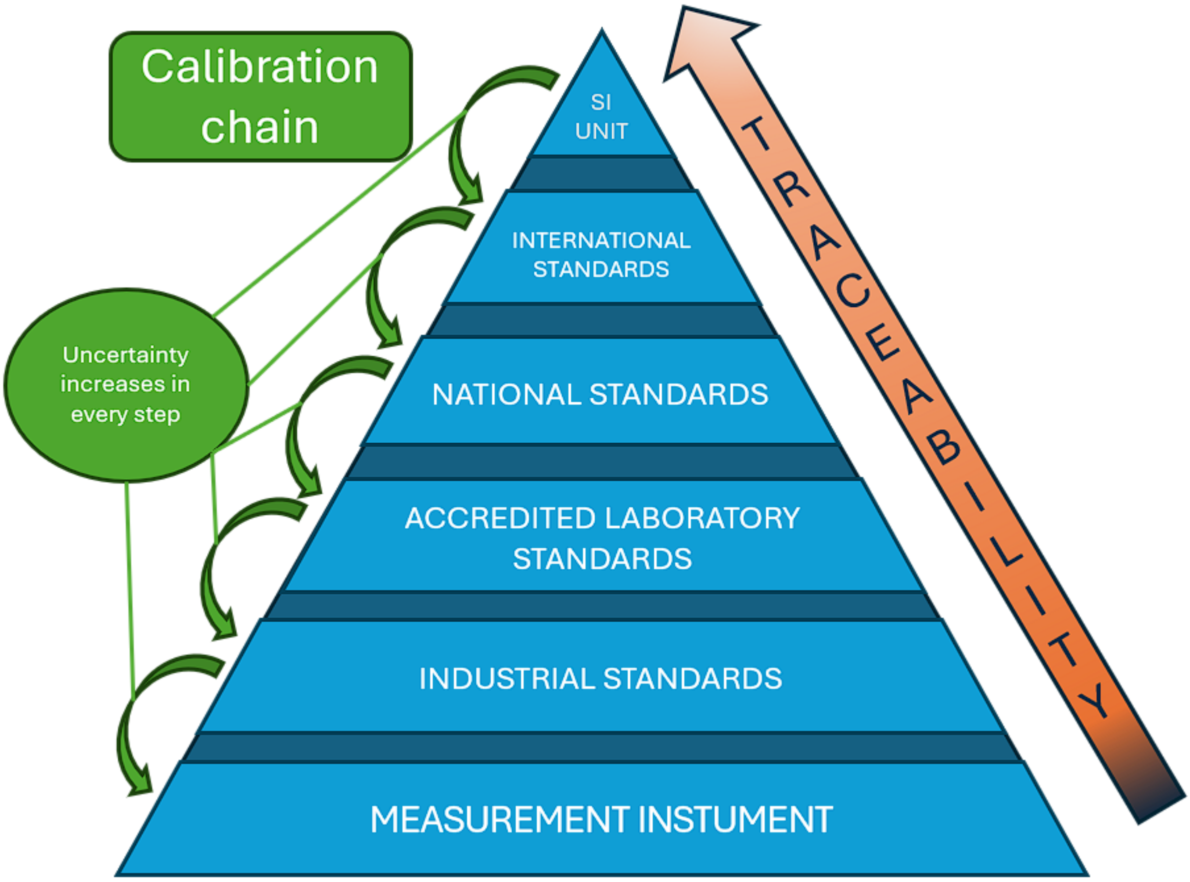

Figure 6 Calibration chain from SI units to the measurement device.

4 HFM calibration methods and possible reference standards

To use different Heat flux meters in different environments and to get comparable results, a standard calibration procedure and reference standard are needed. In current state there is a lack of reference standards for heat flux that lead to metrologically non-traceable results, and for obvious reasons that is unwanted. For example, There are only a few reference standards from a couple of national metrology institutes (NMIs) that generate a low, under 100 W/m^-2, heat flux. [1,23]

Nowadays the heat flux meters are calibrated using the temperature, and the ITS-90- standard for it, and Fourier law of heat conduction because the lack of reference standards for heat flux [9]. Below, a couple different calibration methods are presented for heat flux meters that could also be used to generate a uniform heat flux by conduction and therefore could be used as a reference standard for heat flux.

4.1 Guarded hot plate apparatus

While there is no direct standard or reference standards for heat flux, there is an ASTM C177-13 standard called “Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of The Guarded-Hot-Plate Apparatus”. The standard itself is a standardised method for measuring thermal resistances and heat fluxes but to measure thermal conductivity from the Fourier’s law of heat conduction (Equation 2), the temperature difference and heat flux must be known. It is also worth noticing that thermal resistance does not include the thickness of the specimen like thermal conductivity does, so to get the thermal conductivity, the thickness is divided with the thermal resistance value. Because the measurement is done with Guarded-Hot-Plate (GHP), it means that the heat flux must be close to uniform and known and therefore it could be used to generate a reference standard for heat fluxes, if the heat losses were known. [24,25]

The Guarded-Hot-Plate methods idea is to create a known and uniform heat flux to the tested specimen, so that the specimen’s thermal conductivity can be achieved. GHP can also be used to calculate heat flux with known thermal conductivity, like it can be seen in Fourier’s law of heat conduction. Evidently, some kinds of thermometers are also needed to capture the temperature differences across the specimen. There are two different GHP setups that are called single-specimen and two-specimen GHPs. Both of them are moderately different but the working principle is still similar. [25]

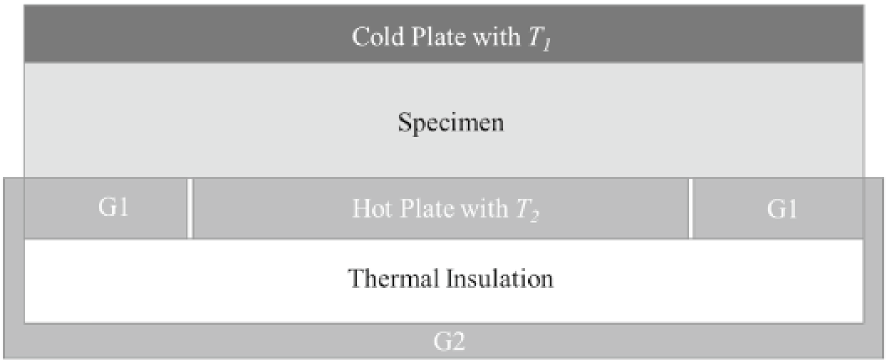

Figure 7 Single-specimen GHP, with two guard rings. (Correct use of GHP)

In Figure 7 the single-specimen GHP is presented with side guard rings G1 and a insulation layer under the hot plate with guard heater G2 under it. The idea of the guard rings and heaters is to make the heat flux one-dimensional with cancelling all lateral and downward flow. The heater helps with that because it is heated to the same temperature than hot plate and therefore no heat transfer should happen. In the single-specimen version there is no guard heater to reduce lateral heat flow but in the two-specimen version there are also side guard heaters after the G1 guard rings. When the heat flux is uniform and one-dimensional, Equation 8 is used to calculate the thermal resistance. Where A is the area of the hot plate and P is the applied heating power.

$$R = \frac{A*(T_h - T_c)}{P} \tag{8}$$

While there is no thickness in the equation, the ASTM C177- standard covers only specimens with thickness up to 5 cm and other standards regarding thermal conductivity cover the thickness to 10 cm. [25]

Working principle of the GHP is absolute so it does not need calibration to work but without calibration the measurement values can vary from the real values and that is why the measurements won’t be traceable. There are ways to calibrate GHP that we will discuss later but the important thing is the uncertainties. The biggest source of uncertainty is heat dissipation which can occur when the thermal guards temperature slightly differs from the heaters temperature or when heat dissipates to the ambient. Other uncertainties come from thermometers not being accurate and heat expansion of the specimen so that the area and thickness changes. In well calibrated GHP those things have been noticed and considered. [25]

4.2 Calibration of thermopile gauge (9.5 to 8 kW/m^2)

In an article Pountney et al. [9] present a calibration method for thermopile heat flux gauges with a heat flux range of 0.5 to 8 kW/m^2. The gauge itself is same than earlier presented in Figure 2 with 54 thermoelectric pairs. In the study they derived a formula for heat flux from the Fourier law and other voltage-temperature formulas as follows:

$$q'' = \frac{k}{\Delta y} * \frac{V}{n(C_1 + 2C_2 * T_{avg})} \tag{9}$$

Where the C_1 and C_2 are coefficients of that will differ from the thermocouples used. In this study they were obtained with from a reference data. To measure and calibrate the HFM, average temperature and output voltage are needed. In calibration the heat flux is known, and the focus is on the voltage and temperature. Assuming the lateral temperature to be negligible, the temperature can be measured with one thermocouple perpendicular to the gauge. [9]

After more deriving the following equation for calibrating the gauge and getting the calibrated sensitivity is created. Where, R is the relation between the thickness of the insulation layer and the thickness of the whole gauge and T_{s1} is the heated side of the gauge that can be seen in Figure 8. [9]

$$S = \frac{V}{q''} = \frac{\frac{n}{2}(C_1 + 2C_2\,T_{s1}) + \frac{n}{2}\sqrt{(C_1 + 2C_2 T_{s1})^2 - 4\,\frac{C_2}{nR}V}}{\frac{k}{\Delta y}} \tag{10}$$

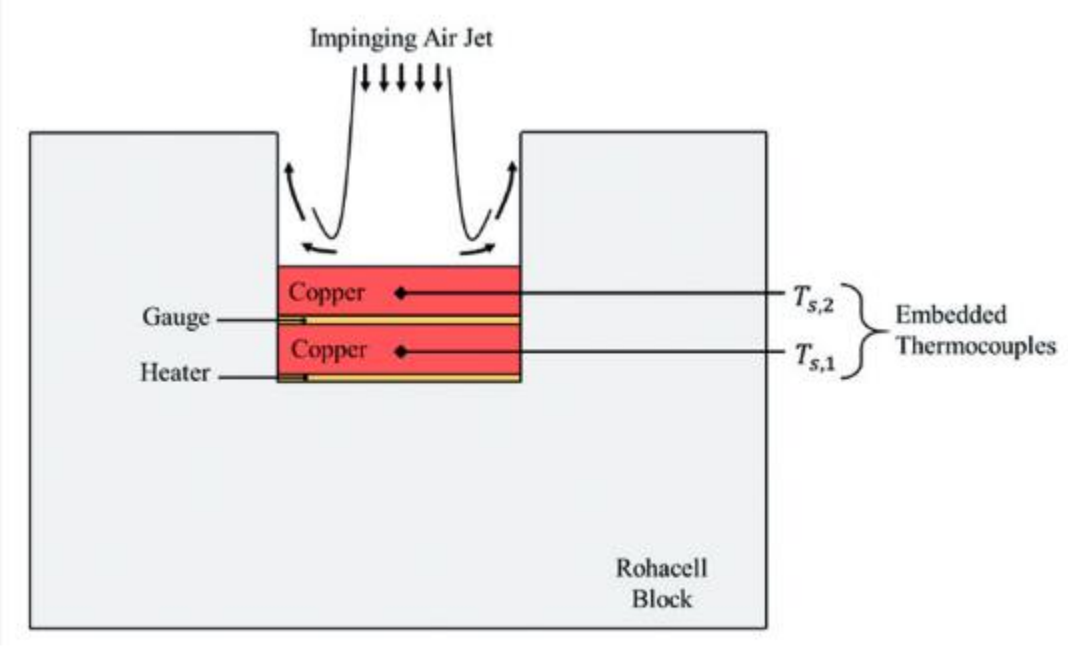

Figure 8 Heat flux gauge calibration setup [9]

The setup for calibrating two thermopile heat flux gauges at the same time is presented in the Figure 8. The setup followed the same working principle than the guarded hot plate system. It consisted of a block of Rohacell foam that has low conductivity ($k = 0.03\ W/mK$) and in the top centre of the block was a hole where the calibrated gauges were placed. In the bottom of the hole there was a thin film resistance heater for constant heat flux (up to 8 kW/m^2) and on top of that heater there were the gauges next to each other in between of 10 mm copper plates that have large thermal conductivity. Embedded thermocouples were installed in the copper plates to measure the temperature and calibrated with a platinum resistance thermometer. The voltage output from the thermocouples and gauges were measured with high resolution voltage meter. To reduce contact resistance between each block, so that equation 9 applied, silicone grease was used. Lastly the exposed layer of the upper copper plate was impinged by a controlled air jet that could be used to control the upper temperature. [9]

The calibration method was pure conduction since there was no fluid between the copper plates, heater and the gauge, and that way Fourier's law could be used. Also, no significant lateral conduction appeared because of the copper's high conduction coefficient. With the setup temperatures from top and bottom, heat flux and output voltage could be controlled and measured with known uncertainties. The air jet controlled the temperature with changing its velocity so that air temperature could be between room and 110 $°C$ with that the temperature of the gauge could be controlled separately from the heat flux. [9]

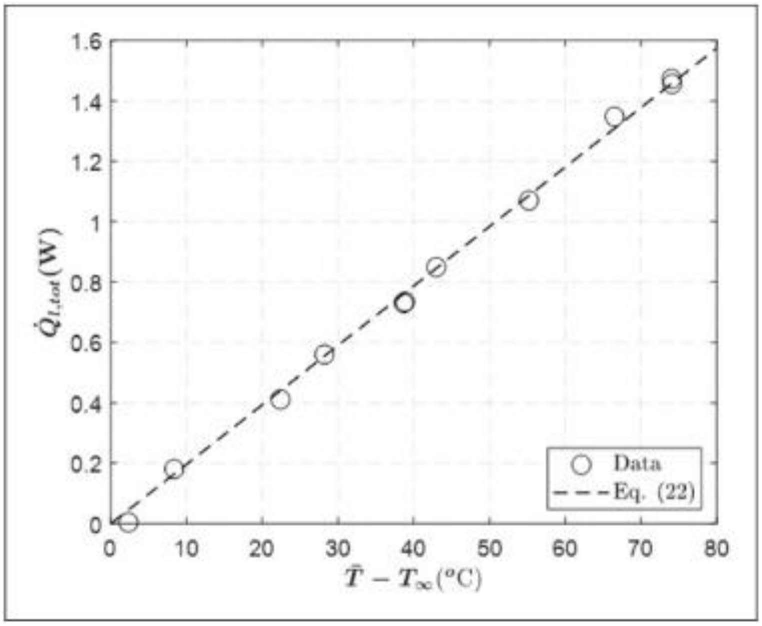

Figure 9 Total heat loss and temperature difference between ambient and heater. [9]

Because the Rohacell block is not an ideal insulator, some of the heat flux could still conduct through it. That is why they did experiments of the heat losses from the bottom of the block and heat losses through the gauge. The variation in total heat losses to temperature difference between the heater and ambient point can be seen in Figure 9 and notice that it is linear. With those values the total rate of heat transfer could be calculated with the following equation. [9]

$$Q'' = P - Q_l'' \tag{11}$$

Where P $[W]$ is the power produced to thin film heater and Q_l'' $[W]$ is the calculated heat loss from the bottom of the Rohacell block that was calculated from the total heat loss from Figure 9 and the heat loss through the gauge. The heat flux is then the total heat rate divided by the gauges area. The most important uncertainty of the calibration came from the evaluation of the heat losses. In this calibration method they estimated the heat loss to be at its highest. [9]

4.3 Calibration of thermopile gauge (5 to 100 W/m^2)

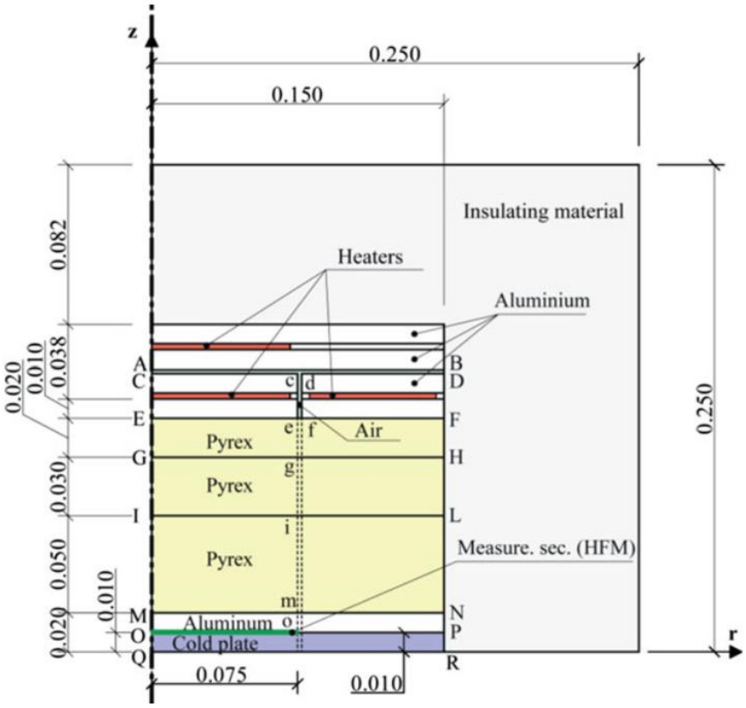

Figure 10 Sketch of the calibration setup for HFM [1]

The prior paragraph dealt with relatively high heat fluxes. In this paragraph, a lower heat flux that is between 5 W/m^2 and 100 W/m^2 is considered with F. Arpino et al. article [1] where they suggest a standard calibration system for heat flux meters. The calibration is done with an absolute method which means that energy was used directly and not for example determining the temperature difference. The prior article also did that alongside the relative method with using the temperatures. The absolute method can be done in example if the power and losses of a heater are known, and the heat loss cross section is known. It would be absolute method to use the reference standard for heat flux. [1]

The calibration setup in Figure 10 is similar to the working principle of the guarded hot plate and the higher heat flux calibration study. It still has small differences in the working principle. The apparatus consists of temperature controlled cold side that is controlled by water cooling the plate. On top of the cold plate, the to be calibrated HFM is placed with a filling material that has the same conduction coefficient. Then like in the previous apparatus, aluminium is placed because it has a high thermal conductivity. The aluminium plate is followed by three layers of different thickness Pyrex glass with a known and certified thermal conductivity so that the heat flux can be estimated from temperature difference. That differs from the previous apparatus where the heat flux was calculated straight before and after the HFM. After the Pyrex layer there are one electric heater on the right and two on the left, and aluminium plates. Like it can be seen in the Figure 10, a vertical air layer is in the middle of the apparatus to cancel any lateral heat flux generated and that is also why one heater is on the right side of the air insulation layer, to prevent lateral heat flux. To calculate heat fluxes from the temperature differences, resistance thermometers are placed next to the heaters and both sides of the Pyrex layer. [1]

The calibration can be done with sensitivity equation (Equation 6) because the heat flux is uniform, one dimensional and known, and the output voltage is known. Calibration could also be done with the Fourier law and the temperature difference. The heat flux values run through the test were 10, 50 and 100 W/m^2, respectfully. The uncertainties were highest (0.41 %) when the heat flux was low but still didn’t go over 0.5 %. Results also showed that having the side thermal guard temperature controlled, had a minimizing impact on the uncertainty of the generated heat flux. [1]

5 Results and discussion

5.1 Results

The purpose of this thesis was to introduce the need for heat flux reference standard by conduction and present a couple of examples how that could be done. It was established that there is no international standard for heat flux, like for example Temperature and Metre has, and only a few existing reference standards from NMIs [1]. To calibrate HFM with low uncertainty and good traceability, a reference standard for heat flux is needed.

The uniform heat flux by conduction that the reference standard needs, can be obtained with different setups that use the same principle than GHP. The setup that used Rohacell foam as insulation (Figure 8) calculated the major uncertainty that was from evaluating heat losses. The setup that generated low, under $100\ W/m^2$, heat flux, has an absolute method for calibration meaning that only heat flux and voltage can be used and no need for temperature measurements.

5.2 Discussion

The reason behind why reference standard for heat flux hasn't been made might be due to the fact that heat energy cannot be measured directly from one point and only heat transfer can be measured between points. Because of heat transfer between points heat dissipation will occur and the method for heat transfer can change which is most likely one of the reasons why such standard hasn't been made yet. Other reason could be that heat flux can be also calculated indirectly with the temperature difference and Fourier law of heat conduction. There probably would also be need for many different reference standards since the heat flux can change with the size and thermal conductivity of the material, and also because the different heat transfer methods.

Generating the reference standard for heat flux by conduction should be possible with an accurate setup that follows the setups done in calibration section where heat losses have been considered. The uniform heat flux would only suite flat HFMs and not anything bigger or insulator. Naturally with the reference standard measurement conditions would be stated.

In future the generation of reference standard for conduction could be started and someday the reference standard for heat flux would be international standard adopted by a standard organization. Also, the reference standards for radiation and convection could be generated.

6 Conclusion

This thesis introduced the need for reference standard by conduction and suggested a couple of ways of doing the standard. Before going into the possible ways of creating the heat flux, some core information, like HFM and its applications, needed to be familiarized in chapter 2. After that, fundamental knowledge about standards and calibration of the HFM were presented in chapter 3 to understand why traceable reference standards are needed. After laying the groundwork, a couple of different solutions for achieving a uniform heat flux via conduction across different heat flux ranges were presented. These solutions could be utilized in the future, when creating the reference standard. The problems with generating the standard and reasons why the standard hasn’t been made yet might be related to heat dissipation in the heat transfer process that can change depending on the size of the specimen and to the fact that heat flux can also be calculated with the temperature difference.

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