



Temperature Distribution Analysis on the Surface of the Radiator: Infrared Camera and Thermocouples Results Comparison

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Abstract: The experiments conducted in a didactic laboratory of the Kielce University of Technology involved temperature distribution measurements on the outer surface of a steel radiator using a thermal imaging camera and thermocouples to compare both investigation methods. The research included registering the parameters for a specific period for each of the four different medium flows. Graphs present the results with the division of the radiator into eight thermal fields. The results present the differences in temperatures between 1.78°C to 3.65°C. The non-contact method with an infrared camera seems more accurate since it is precise for surface temperature measurement.

Keywords: radiator, thermal analysis, thermal imaging, thermocouples

1. Introduction

Most of us spend our daily time in the interiors of the building. We sleep, spend some of our free time and even often work inside different types of rooms. One of the most important factors during that time is our general sensation, named thermal comfort, which ASHRAE (ASHRAE 2013) defined as: "the condition of mind in which satisfaction is expressed with the thermal environment". A proper balance was required to analyse the function between the surrounding environment and the person's thermal comfort, and the Fanger model proposed the predicted mean vote (PMV) index. The scale ranges between -3 to +3 depending on the cold or hot conditions. The approach includes the heat transfer between the occupant and his environment (Stokowiec et al. 2022). The environmental parameters are air temperature, mean radiant temperature, relative humidity and air velocity. As it can be concluded, the temperature inside the room (air and radiant) strongly influences our sensations.

That is why to predict personal thermal feelings, it is necessary to conduct experiments on the source of the proper temperature level inside the room. When analysing the winter season, the heating season in particular, the heating system is important. The elements that transfer the heat to the room interior are heaters. Depending on the heating media, they can be water / steam / electric or gas. On the other hand, we can divide heaters into convection, that work under the principle of heated air motion or radiant, that heat the surfaces around. The materials used for their production are cast iron, aluminium or steel. They can be manufactured as plate, tinned tubes or sectional radiators.

Many investigations have been conducted to observe the phenomena occurring in the area of the operating radiators that influence the personal comfort system to extend acceptable comfort zones. For example, results from a survey conducted in China revealed (Du et al. 2020) that the feet and lower body parts were the most preferred parts to be heated in winter. Therefore local heating device was designed to supply warm air to subjects' feet and calves directly. For the experiments, 20 subjects (10 males and 10 females) were randomly recruited.

Radiant heating was also compared to other systems, such as all-air systems (Karmann et al. 2017); in that case, they provide equal or even better thermal comfort. In the case of convective and radiant heating systems, no significant thermal comfort difference was observed (Lin et al. 2016). Radiant electric heaters situated overhead provide localised heat in historic buildings (churches) without affecting displayed painted walls or works of art (Samek et al. 2007). Radiant heaters are most commonly used in the case of any large-cubage building. However, they can also be gas-fired with the possibility of additional heat energy recovery from the flue gases of radiant gas heaters (Dudkiewicz & Szałański 2019).



The temperature stratification was much higher during the research of convective heaters compared to floor heating systems, but still not significant enough to change the thermal comfort vote. The reduction of temperature stratification can be achieved using heating from the floor and cooling from the ceiling (Causoen et al. 2010). The opposite situation results in high discomfort due to the great temperature stratification (d'Ambrosio Alfano et al. 2014). Moreover, the air temperature stratifications depending on the heating systems may differ. During the experiment, the convector achieved the worst air temperature stratification (Legera et al. 2018).

The tests were also conducted for radiant temperature distribution patterns generated by radiant heaters with different power outputs and suspended at different angles (Dudkiewicz & Jezowiecki 2011). The results refer to parameters characterising the thermal comfort of people in large-capacity halls. Other research analysed the heat enhancement using additional coatings or mesh structures (Chatys & Orman 2017, Dąbek et al. 2019) or multi-component liquid media (Koshlak & Pavlenko 2021). Finally, other researchers present thermodynamic analyses (Koshlak & Pavlenko 2019).

The studies of radiant panel heaters evaluated the perception of the indoor environment. They experimentally investigated the comparison with conventional portable natural convective heaters, concluding that situating the panel heaters on the wall facing the window and on the wall close to the window provides the best operative temperature distribution in the office room (Ali & Morsy 2010).

Numerous examinations have been performed on convective-radiative heat transfer: the effect of turbulence has been modelled (Wang et al. 2014), indicating that the ratio between convection and radiation is directly proportional to the Grashof number and inversely to the surface emissivity. Turbulent natural convective energy transport above a heated element phenomenon has also been conducted statistically, dividing the turbulent flow into three regions according to power spectrum distribution analysis (Zhang et al. 2016). The research also noted that the enclosure geometry greatly impacts determining the circulation configuration and heat transmission inside the enclosure (Miroshnichenko & Sheremet 2018).

The underfloor heating system is also widely analysed and described in the literature. The studies are mainly grouped into two fields: an economic analysis (Karimi et al. 2019) and experimental and numerical research of system design and performance (Magni et al. 2019). Recently, interest has grown in the aspect concerning energy transport and liquid circulation (Stepan et al. 2021).

Not enough theoretical nor experimental analyses have been recently performed to research the convection heaters as an element of a central heating system in the building. The studies include estimating preheating time in buildings that are not continuously occupied, such as shopping malls, office buildings, and residential houses (Sun et al. 2022). Thermal analysis based on the obtained experimental laboratory results was used to assess the heating efficiency of heaters with parameters: different power consumption, geometric shape and dimensions (Bertolin et al. 2015).

The environmental protection issues, including carbon dioxide and other pollutants emissions reduction, involve the thermomodernization practices (Wciślik 2017) with the energy efficiency of the heating system and the economic analyses required.

The heat transfer phenomenon can be described by three modes: conduction, radiation or convection. Contactless methodologies are applied to analyse the surface temperature distribution. The most popular approaches involve thermal imaging procedures to investigate thermal bridges and excess heat losses in buildings (Stokowiec & Sobura 2022). The basis of infrared camera operation is the radiation process observed for every body with a temperature above absolute zero. Therefore, the infrared camera software implements the Stefan-Boltzmann law for temperature value calculations. Other devices applied for temperature measurement require contact with the investigated object and involve the conversion of heat conducted to the thermoelectric voltage. These are called thermocouples.

Due to the scarce scientific and academic achievements evaluating convection heaters, the paper presents a thermal study with the experimental results of convection heaters incorporated in the laboratory installation simulating the real central heating system operation. The scope of the experiments was to conduct parallel investigations of surface temperature on the heater during its operation with two methods: thermocouples/infrared camera and compare the results.

2. Methodology

2.1. Conducted Research and the Testing Device

The research was taken during the heating season in November in one of the lecture rooms in Energies – a laboratory and didactic building that is an intelligent, self-sufficient and modern part of the Kielce University of Technology complex. The tested installation consists of a hydraulic system with an electric boiler

as a heat source, radiators, pumps, and heating pipes with all necessary equipment, such as: shut off valves, regulating valves, and others, as shown in Fig. 1. The system simulates the central heating operation on one outlet and the domestic hot water on the other.

One of the four-panel radiators was connected to the DaqLab2000 data acquisition station using 8 thermocouples to carry out the research. Thermocouples NiCr-NiAl type K with $41 \mu\text{V}/^\circ\text{C}$ sensitivity are used in the temperature range from 200 to 1200°C . The tolerance is $\pm 1.5^\circ\text{C}$ within the temperature range of -40°C to $+375^\circ\text{C}$.

The station recorded the temperature changes on the surface of the tested radiator with a dedicated computer software program.

DaqLab2000 is a measurement system by IOtech equipped with an ethernet interface. The device allows the measurement of analogue signals (8 channels, 16-bit converter / 200 kHz), and frequency measurements (4 channels, 16bit / 10MHz). Additionally, the user gets six digital inputs / outputs available (+24 on DB37 connector).



Fig. 1. Lecture room at Kielce University of Technology with tested installation

At the same time, the infrared camera Testo 890 was located opposite the measured radiator (Fig. 1), and several thermograms were taken during the heating process. For each of the four supply flow rates set during the experiment, the measurements lasted for 4.5 minutes with a 15 seconds interval. The thermal imaging camera used in the research has a resolution of 640×480 pixels, with the SuperResolution technology of 1280×960 pixels. Its thermal sensitivity is $< 40 \text{ mK}$, which allows seeing even the most minor temperature differences. The temperature measuring range is from -20 to 350°C , and the picture refreshes at 33 Hz.

During the experiment, the electric boiler was set to the 50°C flow rate and the system was heated up for several minutes to reach the required temperature. The acquisition station and the THV camera recorded the temperature changes in each field for four different flow rates (0.5, 1, 1.5, 2 l/min) selectable with the rotameter readers and with a duration of 4.5 min each. At the same time, the data of the heating medium on the supply and return side was measured using temperature sensors located as a part of the system. The radiator employed in the testing facility was a cold-rolled steel sheet Radson Integra type 11, one-panel radiator with dimensions $600 \times 600 \times 57$, height, length and width, respectively. Its power is 563W for parameters $75/65/20^\circ\text{C}$ with the bottom left connection as dedicated for this type of radiator. The heater is painted with white colour RAL 9016. The max. working pressure is 10 bar and max. working temperature is 100°C .

The radiator was divided into nine equal fields, and thermocouples were located in the centre of 8 of them, as shown in Fig. 2. Those fields were chosen as the best representative of the temperature distribution on the radiator's surface. Eight data acquisition station outlets were available.

The emissivity of the tested object was tested at the beginning of the experiment using tape of known emissivity and defined as 0.92. The tape of known emissivity of 0.95 was applied on the radiator, and using the thermogram taken at the beginning of the experiment and IRSoft software, the emissivity of the radiator's surface was established. That factor was applied to the THV camera during the experiment. Besides the emissivity, the room temperature and relative humidity were measured and implemented into the camera software before the experiment.

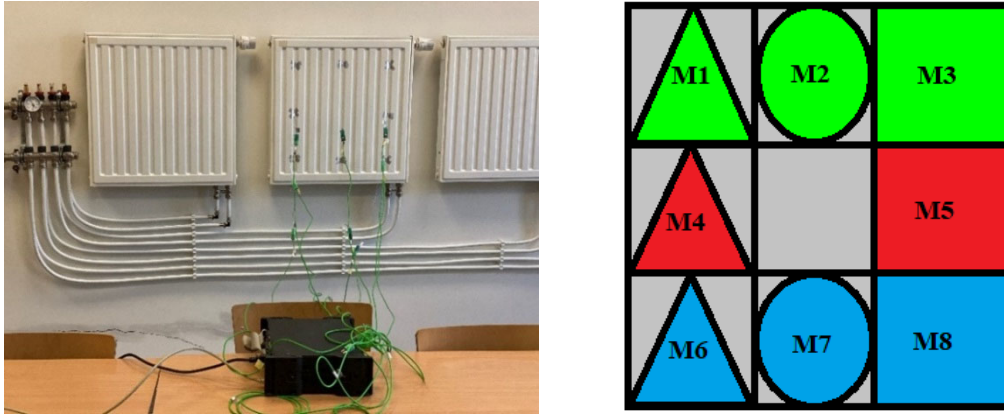


Fig. 2. Tested Radiator with 8 no. field measurement location, actual photo and arrangement of the measured fields

Due to the emerging rays of sunlight, no reflections were considered during the research. Related experiments were conducted by (Orłowska 2020), where the author examined the isothermal face of the Purmo flat panel radiator with a THV camera.

2.2. Results

The infrared camera shows how temperature fields are shaped with thermograms. Fig. 3 is an example thermogram taken at the flow rate of 0.5 l/min, and at 2 l/min, the reddish colours show the hottest temperatures and the green and blue the coldest as appears on the surface on the radiator during the experiment.

Example results obtained from the thermocouples for the 2 l/min flow rate for each of the 8 points measured for the temperature distribution are shown in Fig. 3. The differences in temperature present the flow of the heating medium as well as the proper operation of the radiator concerning the supply/return junction.

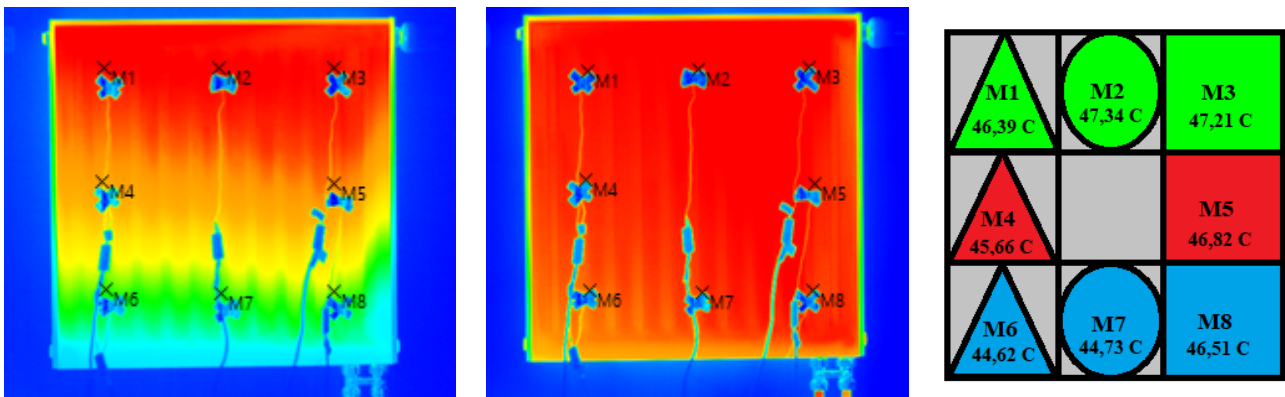


Fig. 3. Thermogram of a radiator with 0.5 l/min and 2 l/min of flow rate and mean temperature results in °C for the measurements taken by thermocouples of a radiator 2 l/min of flow rate

3. Discussion

Based on the results obtained from the measurement series for both the THV camera and thermocouples, temperature distribution as a function of flow rate is shown in Fig. 4, 5, 6, depending on the location of the measuring points of the radiator (upper, middle and bottom).

As shown in Fig. 4, points M2 and M3, located at the upper part of the radiator, are with the highest temperature according to measurements with thermocouples and according to the infrared camera. The mean temperature of the surface of the radiator rises with the flow rate. The M3 and M2 points are the closest points to the main vertical channel that distributes the water inside the radiator and are the highest values. The differences in temperatures between the M3 and M1 points are between 0.74 and 1.3°C with thermocouples and 0.36 and 1.02°C, respectively, with the infrared camera.

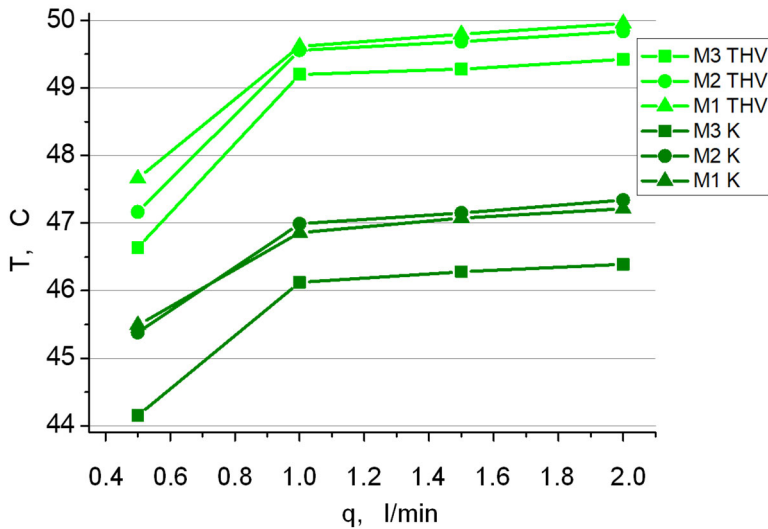


Fig. 4. Temperature distribution in the upper part of the radiator as a function of flow rate (THV – thermal imaging camera, K – thermocouple)

In the middle part of the radiator, only two fields were measured with thermocouples. The M4 point is located on the left side of the heater, and M5 is on the opposite end. Therefore the difference in temperature between the two is greater and is around 1°C with the min. and max. values of 0.74 and 1.15°C, respectively (Fig. 5).

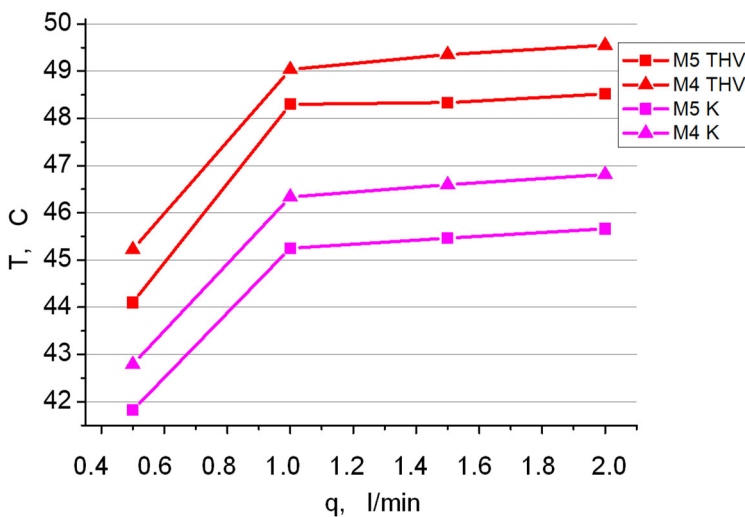


Fig. 5. Temperature distribution in the middle part of the radiator as a function of flow rate (THV – thermal imaging camera, K – thermocouple)

Fig. 6 represents the bottom part of the examined heater, which is the coolest area in the radiator, according to the research. The temperature changes between the M8 and M7, and M6 are greater than in the middle part and range from 0.55 to 2.19°C. The temperature differences between the points are lower according to a thermal imaging camera than thermocouples, despite the higher temperature rates achieved by an infrared camera.

The mean values were calculated for all three parts of the tested radiator, and Fig. 7 represents the results. The analysis of the temperature distribution proves that the surface is not isothermal for both methods. The greater the flow rate, the changes in temperature difference are smaller. Still, with its minimum flow rate 0.5 l/min value, the dT is even 5.96°C with thermocouples and 5.82°C with the infrared camera between the fields (regarding the mean values for each of the part studied).

The overall mean temperature surface of the radiator is 44.92°C and 47.66°C for each research method. The standard deviation for the mean temperatures depending on different flow rates was calculated as 2.32 regarding thermocouples and 2.43 regarding the infrared camera experiment. Fig. 8 illustrates characteristics of the temperature difference between the two measurement method for each of the 8 points and show that the temperature difference is significant, and at some points, it reaches even dT 3.65°C.

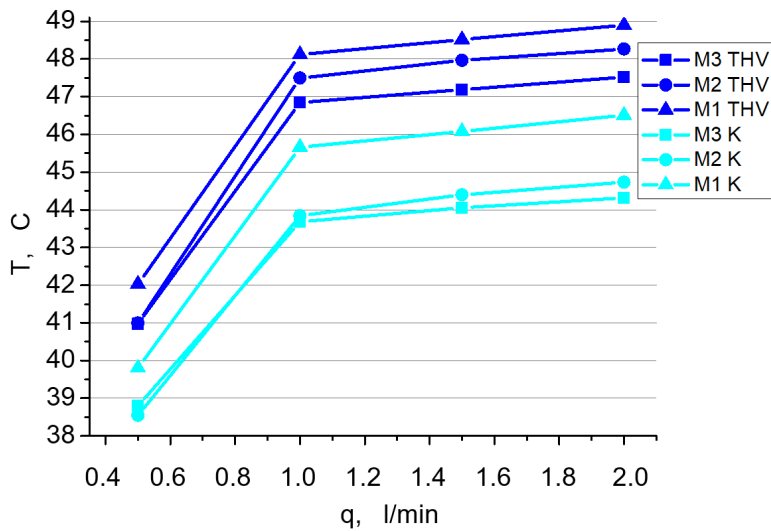


Fig. 6. Temperature distribution in the bottom part of the radiator as a function of flow rate (THV – thermal imaging camera, K – thermocouple)

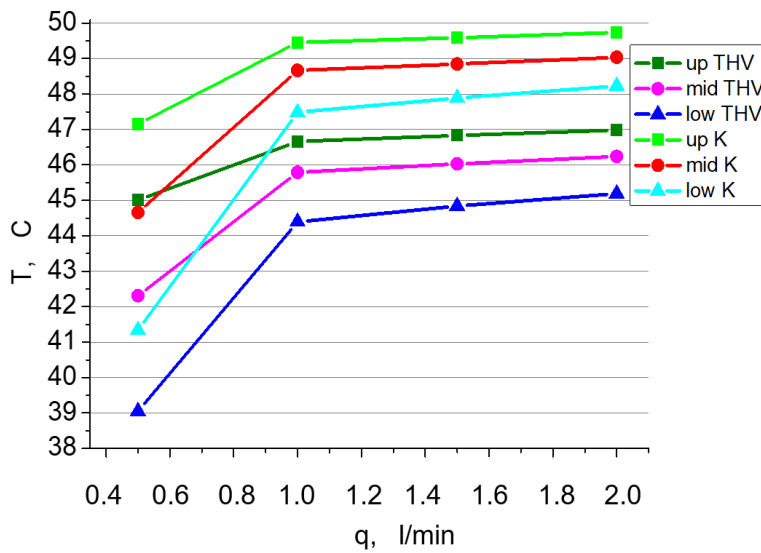


Fig. 7. Mean temperature distribution in the top, middle and bottom part of the radiator as a function of flow rate (THV – thermal imaging camera, K – thermocouple)

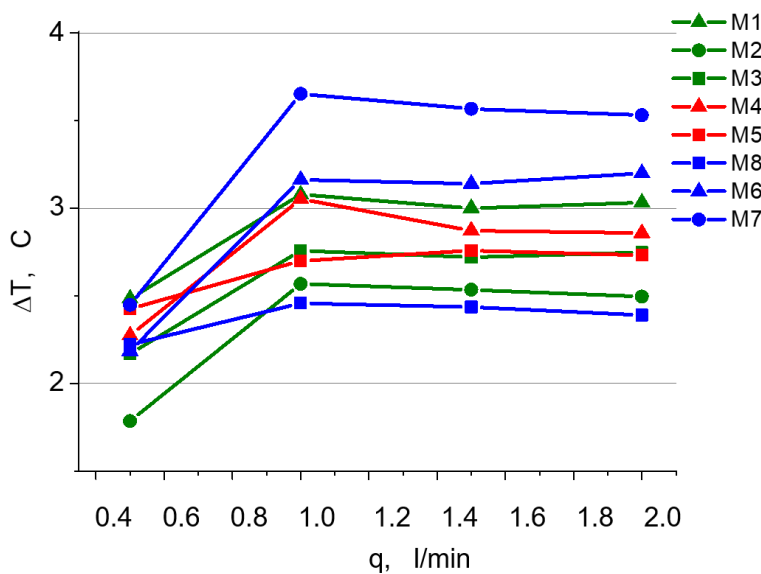


Fig. 8. Characteristics of the temperature difference between the thermocouples and the thermal imaging camera measurements for M1 to M8

Temperature changes over time are shown in Fig. 9 for the THV camera and thermocouples, respectively. As noticed in both diagrams, temperatures increase equivalently with the flow. The highest temperature during the experiment was noted in points M3, M2 and M5 for each method. The curves were prepared for a water flow of 2 l/min, which was the final test taken. During the experiments, the max fluid flow rate was reached. However, the diagrams prove the non-isothermal temperature distribution on the heater. The standard deviation was determined for each of the points from M1 to M7, considering the flow rate change. Regardless of the method, SD decreased with increasing flow rate and ranged between 0.08-2.52 and 0.1-2.94 for thermocouples and THV, respectively.

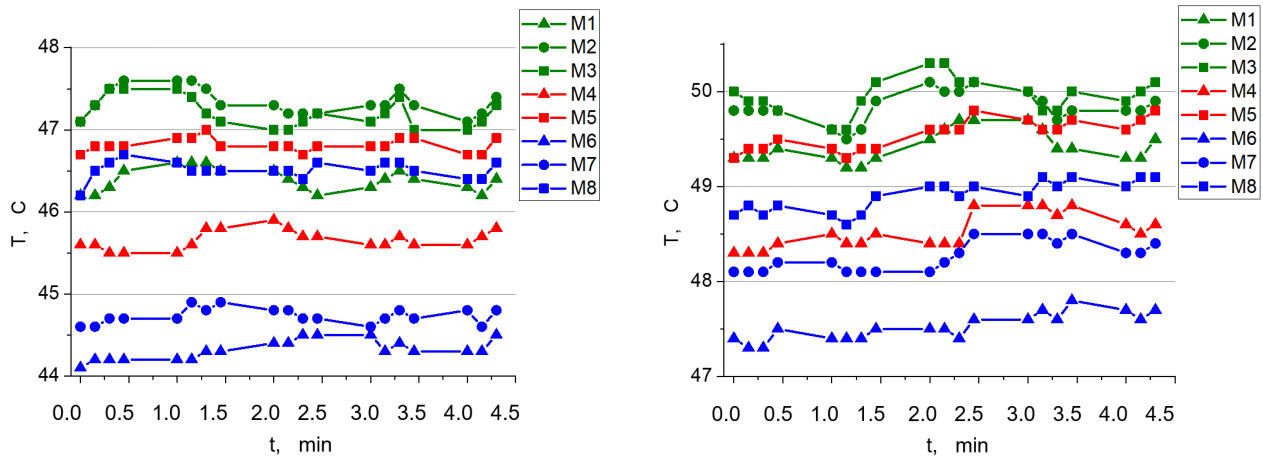


Fig. 9. Temperature change for 8 points M1 to M8 for 2 l/min water flow with the infrared camera and thermocouples measurements

One of the factors influencing the temperature distribution is the connection of the radiator to the hydraulic system. In the case of the right side bottom one, we observe a high impact, especially with the min flow rate required by the radiator. The radiator's right side and upper side are warmer and heated much faster than the rest of the radiator. This greatly impacts the process of convection and affects the thermal comfort of the occupants inside the environment. The internal air temperature was monitored during the process, and the temperature increased from 23.6°C to 25.5°C with the max. flow rate of 2 l/min. The outside air temperature was around 10°C.

4. Conclusions

Between the two methods, the infrared camera and thermocouples, there are differences in temperatures of the radiator's top, middle and bottom parts with the min. of 1.78°C and max. of 3.65°C. The phenomenon observed results from the various operation principle (either radiation or conduction heat mode) and the measurement accuracy of each device. The contactless method with the THV camera seems to be more accurate. The thermal imaging method, despite the camera accuracy and the examined emissivity factor, has given the highest temperatures. There are numerous reasons for that, including the distance between the object and the infrared camera. The other one is the direct sunlight that appeared during the experiment, and the room was not fully shaded. Moreover, it required to analyse of the mechanical ventilation and floor heating systems installed in the room due to the possible increase in the surface temperature of the panel heater. Based on the conducted study, further analysis of the measurement uncertainty of the devices can be performed, as well as thermal comfort analysis of the occupants with the radiators as a main heating source.

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