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Performance evaluation of radiant baseboards (skirtings) for room heating – An analytical and experimental approach

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HIGHLIGHTS

- Thermal performance of radiant baseboards (RBs) used for space heating was analyzed.
- The proposed heat output equation can be used with confidence for RBs heaters.
- The heat transfer ability of RBs was 50% higher than that of panel radiators.
- The heat emission from RBs increased by roughly 2.1% per centimeter of height.
- The RBs of maximum height should be used for water supply temperatures below 45 °C.

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ABSTRACT

The aim of this study was to investigate the thermal performance of the hydronic radiant baseboards currently used for space heating in built environments. The presently available equations for determination of heat outputs from these room heaters are valid for a certain height at a specific temperature range. This limitation needed to be addressed as radiant baseboards may be both energy and cost efficient option for space heating in the future. The main goal of this study was therefore to design an equation valid for all baseboard heights (100–200 mm) and excess temperatures (9–60 °C) usually used in built environments.

The proposed equation was created by curve fitting using the standard method of least squares together with data from previous laboratory measurements. It was shown that the predictions by the proposed equation were in close agreement with reported experimental data. Besides, it was also revealed that the mean heat transfer coefficient of the investigated radiant baseboards was about 50% higher than the mean heat transfer coefficient of five conventional panel radiators of different types.

The proposed equation can easily be used or programed in energy simulation codes. Hopefully this will help engineers to quantify more accurately the energy consumption for space heating in buildings served by radiant baseboards.

1. Introduction

Different types of hydronic and electric systems are currently used for space heating in the Swedish residential sector [1]. In hydronic systems, heat is usually distributed by conventional hot-water radiators while in electrical systems various distribution arrangements are used. Between 1960 and 2010 electrical systems were predominantly used for space heating in Swedish single-family dwellings. Accordingly, approximately 70% of the country's single-family houses either used or could use electricity for space heating in 2001. By that time, around 34% of 1.6 million Swedish single-family houses were heated by direct-acting electricity and water-based electric heating [2]. In addition to these 34%, another 36% had electric heating as an alternative heating system [2]. This means that about 1.12 million of country's single-family houses used electricity either as sole or as a supplementary heating system in 2001.

In order to reduce the electrical peak loads and energy consumption during the heating season, the Swedish government has undertaken a number of measures over the last decades. Thus, during the period between 2006 and 2010 the homeowners could have been refunded with up to 30% of their conversion costs, when

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Nomenclature

Latin letters

A	area m^2
a	constant in Eq. (3) -
b, c and d	exponents in Eq. (3) -
c_p	specific heat capacity, J/(kg °C)
d	diameter, m
H	baseboard height, m
h	height of waterway, m
f	flow friction factor between water and waterways
K	heater constant, W/°C^n
k	equation number
L	length, m
$\dot{m}$	mass flow, g/s
n	temperature exponent or number of samples
P	heat output/thermal power, W
q	heat output per m, W/m
Re	Reynolds number
SEE	standard error of estimate, W/m
U	total heat transfer coefficient, W/(m^2 °C)
v	velocity of water, m/s
w	width of waterway, m

Greek letters

ε	absolute inner surface roughness, m
θ	temperature, °C
Δ	percentage difference, %
$\Delta\theta$	excess temperature = mean temperature difference between room heater and room air, °C
Δp	pressure loss, Pa

Subscripts

ave	average
calc	calculation by Eq. (9)
eq	equivalent
max	maximum
ref	reference value
room	room
rtn	Return
supp	supply

conventional radiator types

10	single panel
11	single panel + single convector plate
21	two panels + single convector plate
22	two panels + two convector plates
33	three panels + three convector plates

converting from electric to alternative heating systems [3]. As a result of conversions between 2006 and 2010, the electrical energy consumption for space heating in the residential sector has been decreased by 476 GWh/year. It was estimated that about 34% of this total saving could be directly attributed to the government's financial support [4].

In addition to the above-mentioned, the installation of heat pumps in Sweden increased greatly between 1994 and 2011. As a result of this the one-millionth heat pump was put in operation in single-family houses in 2010 [5]. The Swedish Heat Pump Association has estimated that by that time approximately half of the installed heat pumps were of the air-to-water and closed-loop types [6]. By 2010, these two heat pump types stood for approximately 490 MW of installed nominal power in Sweden [7].

As is generally known, the efficiency of the heat pump in a heating system is strongly dependent on the supply water temperature of the system. The lower the supply water temperature, the higher the efficiency of the heat pump. Up to now, the supply temperature of the heating system in Swedish single-family houses was usually decreased by increasing the number of room heaters. Although various types of the room heaters were available on the market at that time, conventional radiators were mainly used for heat distribution in dwellings heated by heat pumps. Similarly, conventional radiators were also predominantly used when converting from direct-acting electricity to hydronic heating. Despite the fact that perhaps some other types of room heaters could have been more appropriate option, especially for homes served by heat pumps.

It should also be noted that Sweden is not alone in making efforts to improve the efficiency of the heating systems. Different research groups in several European countries are also currently working on finding methods to improve thermal efficiency of the heating systems in residential buildings. Meir et al. [8] presented a new method for temperature control in buildings with floor heating. The presented control method decreased the response time and resulted in closer follow of changes in outdoor temperature. Consequently, this control method was more energy efficient than the traditional one with conventional thermostats. The joint influence of the enhanced emissivity and the surface roughness of a wall behind a hot radiator was studied by Shati et al. [9]. They found that the total heat output from the radiator could be increased by 26% through the use of a high emissivity saw-tooth wall surface. Pinard et al. [10] studied the possibility to enhance the heat output from a room heater using induced stack effect. Reported results suggested that this method could improve the total heat output by approximately 24%, at maximum. Badescu [11] investigated the potential of using active solar heating in a passive house. He found that 62% of the total annual heat demand could be met by this system. Hewitt et al. [12] analyzed performance of an air-source heat pump connected to a radiator system. Not surprisingly, they concluded that low-temperature radiators would increase the heat pump efficiency.

In conclusion, findings from the presented studies clearly suggest that the need for efficient and flexible heating systems is broad.

1.1. Potential of radiant baseboard heaters

A hydronic heating system that is still limitedly used in Swedish residential sector is radiant baseboards (Fig. 1a). The radiant baseboards usually have two waterways. One supply and one return pipe, which are attached to the enclosing metal plate (Fig. 1b). The waterways are also connected by a 180° u-bend at the opposite end of the circuit. The typical height of the radiant baseboards is between 120 and 180 mm, and their length is normally ranging from 8 to 15 m per room. Since enclosing plates have no openings at the front side, the adjacent room air is prevented from passing over the inner part of the unit. Consequently, a large portion of the emitted heat is transferred by thermal radiation [13]. An additional example of radiant baseboards placement in a real-life room is given by Fig. 1c.

Due to their low height, the transferred convective heat flux from radiant baseboards to the room air is high [15]. Also, since radiant baseboards are installed at the base of the walls they are

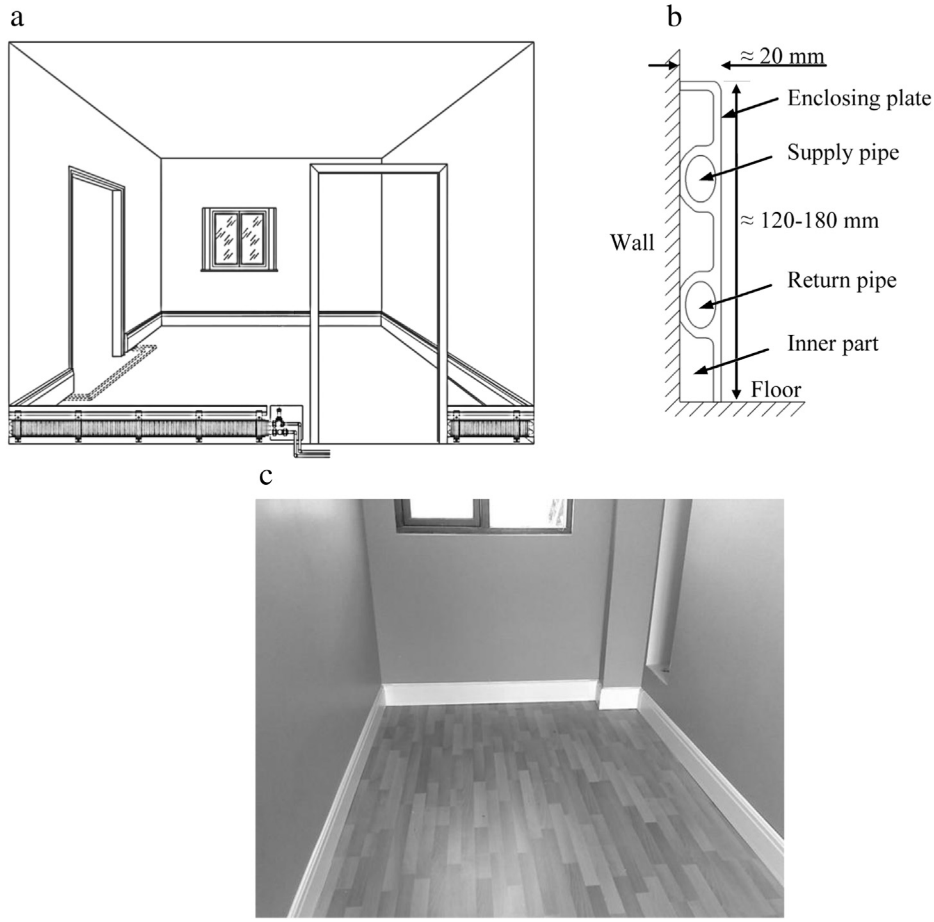

Fig. 1. a. Illustration of the placement of radiant baseboards along the inner periphery of a room [14]. b. The typical dimensions and vertical cross-section of a radiant baseboard heater. c. The installation of radiant baseboards under real-life conditions.

exposed to colder room air along their entire length. This increases the thermal gradient and thus their ability to transfer heat to the room. The cumulative effect of these two characteristics of the radiant baseboards is illustrated in Fig. 2a. As can be seen, the mean heat transfer coefficient of the radiant baseboard is much higher than that of conventional panel radiators. The average heat transfer coefficients of the panel radiators ranged from 7.4 to 9.7 W/m^2 °C, with a joint mean value of 8.4 W/m^2 °C. On the other hand, the mean heat transfer coefficient of the used radiant baseboard arrangement was 12.6 W/m^2 °C. This means that the heat transfer ability of the used radiant baseboard was about 50% higher than that of the selected radiator types.

The total heat output as a function of the length of a 0.185 m high radiant baseboard is shown in Fig. 2b. In the same figure the outputs from two panel radiators of different geometries and types are also shown. It can be seen that 12 m long and 0.185 m high radiant baseboard, gave the same heat output ($\approx$890 W) as a 1.2 m long and 0.5 m high panel radiator of type 22. This means that in a 5 m by 3.5 m room space, the selected radiant baseboards installed along three walls would be able to give the same amount of heat as the above-mentioned radiator type. With these water temperatures the used radiant baseboard arrangement is also powerful enough to cover the heat loss of the considered room space at an outdoor temperature of −17 °C [8]. This temperature level presently corresponds to the design outdoor temperature for buildings with time constants between 24 and 72 h, placed in the central part of Sweden [16].

1.2. Previous studies on radiant baseboard heaters

In contrast to most conventional hydronic room heaters, reliable heat emission data from radiant baseboards is still limited. Usually the data provided by the radiant baseboard manufacturers is both limited and often poorly presented. Consequently, the traceability of the presented data is very difficult or impossible and therefore the validity might be questioned. According to the authors' present knowledge, four reliable reports dealing with heat emission from radiant baseboards have been reported in the recent past. In a previous study [15] we estimated heat emission from 0.15 m high radiant baseboards using well-known relations for natural convection and thermal radiation for a vertical flat plate. Russell [18,19] reported the measured heat outputs from 0.185 and 0.13 m high radiant baseboards. Siegenthaler [20] in his book presented a diagram with heat emission from a 0.127 m high radiant baseboard heater.

Summarizing the findings from previous studies presented in Sections 1–1.3 the following can be concluded:

- There is a need for efficient and flexible hydronic heating systems that can either be used as an alternative or as a complement to existing room heaters.
- The heat transfer ability of radiant baseboards is much higher than that of conventional panel radiators. Radiant baseboards may therefore play an important role for space heating both in new-built and retrofitted buildings.

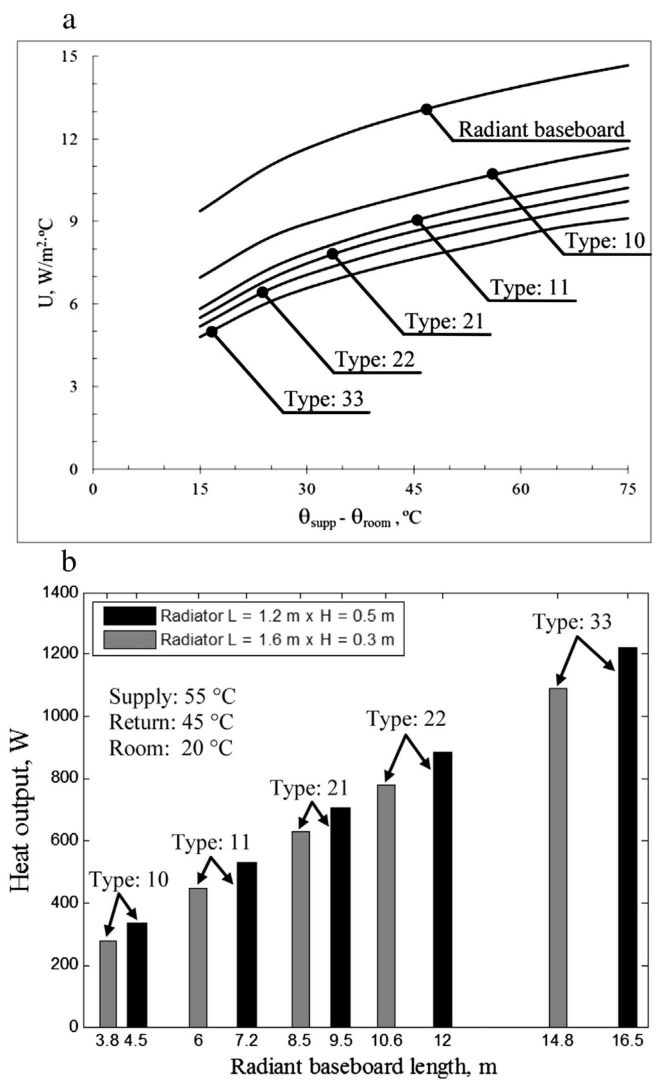

Fig. 2. a. The variation of the mean heat transfer coefficient *U* for considered room heaters [17,18]. The heights for used radiant baseboards and conventional radiators were 0.185 m and 0.3 m, respectively. b. The required lengths of a 0.185 m high radiant baseboard [18] to produce the same heat outputs as the different radiator types of 1.6 m length and 0.3 m height, and 1.2 m length and 0.5 height [17].

- In the previous investigations, the heat emission from radiant baseboards was either measured or calculated at a certain baseboard height.

1.3. Objectives

Therefore, the main objective of this study was to design a reliable equation for estimation of heat output from radiant baseboards. The aim was to design an equation that would be applicable for all baseboard heights (0.1–0.2 m) and excess temperatures (9–60 °C) usually used for radiant baseboards in built environments.

2. Method

2.1. Laboratory measurements

The experimental data reported by Russell [18,19] was used as base for designing the aimed equation. In these two reports, the heat outputs from 0.13 and 0.185 m high radiant baseboards operated at different water temperatures were reported. The heat outputs were measured in a testing chamber of 4 m (1ength) × 4 m (width) × 3 m (height). The tested radiant baseboards consisted of a 3 m long aluminum extrusion with two integral horizontal waterways. The hot-water inlet and outlet were at the same end of the baseboards, and connected with a return bend at the opposite end. Since the radiant baseboards were tested at different water temperatures, all chamber walls except the wall behind the baseboards were also water-cooled. By doing so, the mean indoor air temperature in the chamber was kept at 20 °C. The air temperature was monitored at 0.75 m above the floor level at the center of the chamber. The wall behind the baseboards was also well insulated to prevent heat losses.

The steady-state condition inside the chamber was maintained for at least 30 minutes before starting the measurements. After reaching steady state, the measurement data was automatically logged at 100 second intervals. The heat outputs from the baseboards were determined by measuring: 1) the change of water temperature between inlet and outlet, 2) the water mass flow rate through the baseboards and 3) the air temperature inside the chamber. The water and air temperatures were measured by resistance thermometers, while the water flow rate was measured by a mass flow meter. The air thermometer also had a protecting shield to minimize the influence of thermal radiation from the surrounding walls. All used measuring instruments were calibrated with probes of higher accuracy before testing, see Table 1. The dates of testing for both radiant baseboards were within the time range of calibration validity for all instruments.

It should be noted that the outputs were measured according to European norm EN 442-2 from 1997. This norm defines procedures for determining the thermal power of the heating appliances fed with water or steam at temperatures below 120 °C. In order to hold the license for testing according to EN 442-2, the total precision of the performed measurements in the testing laboratory must be within ±2% deviation of results obtained by other certificated laboratories [21]. Since 2003, this precision level is regularly controlled by a round-robin test at least once a year without prior notice. The precision and the accuracy levels of measurements performed by the Building Services Research and Information Association (BSRIA) testing laboratory was checked regularly according to the above described method. The precision and the accuracy of data used for this study lay within the above-specified range and as shown in Table 1.

2.1.1. Operating water flow rate

The thermal outputs of the radiant baseboards were measured at three water flow rates, 10.6 g/s, 56.0 g/s and 112.5 g/s. In order to decide which flow rate was the most appropriate for the present study, the Reynolds number and linear pressure loss for all three water flow rates were calculated and compared to each other. The

Table 1
The ranges, uncertainties and calibration accuracies of instruments used for measurements in the testing chamber [18,19].

Item	Instrument	Range	Uncertainty	Calibration accuracy
Water temperature	Resistance thermometer	30–90 °C	±0.05 °C	±0.02 °C
Air temperature	Resistance thermometer	19–21 °C	±0.04 °C	±0.02 °C
Mass flow rate	Mass flow meter	10–113 g/s	±0.02–0.04%	±0.02–0.04%
Pressure	Barometer	900–1066 mbar	±1 mbar	±0.02%

calculations were based on the equivalent diameter d_{eq} of an oval cross section, as the waterways of the tested baseboards were elliptical.

From Table 2 it can be seen that the water flow at 10.6 g/s was laminar and generated a pressure loss of 3 Pa/m per waterway. At 56.0 and 112.5 g/s the flow was turbulent and the pressure loss per waterway was 54 and 180 Pa/m, respectively. Based on this, the heat outputs at 10.6 g/s were excluded from further consideration as this flow was not turbulent and thus should be avoided when designing baseboard heating systems [13,14]. Similarly, the heat outputs at the flow rate of 112.5 g/s were also excluded as this flow generated a pressure loss 1.8 times higher than 100 Pa/m per waterway. As this value is presently used as a guideline in dimensioning heating pipe networks [16]. Thus for the current study the heat outputs produced by the water flow of 56.0 g/s were used as reference in designing the aimed equation.

2.2. Equations for estimation of the heat output

In general, heat output from hydronic room heaters is mostly controlled by three parameters: the temperature of the heater surface, the size of the heater surface area and the temperature of the room air. The total influence of these three parameters is normally summarized by a global energy balance, as shown by Eq. (1).

$$P = \dot{m}c_{\mathrm{p}}(\theta_{\mathrm{supp}} - \theta_{\mathrm{rtn}}) = UA\overbrace{\frac{\theta_{\mathrm{supp}} - \theta_{\mathrm{rtn}}}{\ln[(\theta_{\mathrm{supp}} - \theta_{\mathrm{room}})/(\theta_{\mathrm{rtn}} - \theta_{\mathrm{room}})]}}^{\Delta\theta} \quad (1)$$

The magnitude of the heat transfer coefficient U is affected by several factors, such as the material, design, height and operating water temperatures of the heater. Due to this, the theoretical calculation of the U value is normally laborious. For room heaters with a constant surface area, the heat output becomes a function of the heater constant and excess temperature only. Accordingly, the complexity of the right-hand side of Eq. (1) can be reduced to Eq. (2) [13]. In this expression, P represents the total heat output, K is the heater constant and n is the temperature exponent. The values for K and n are not universal and they apply to a certain heater dimension only. Normally they are determined using an experiment-based approach together with regression analysis. For hydronic baseboard heaters, Eq. (2) was also used for estimation of the heat output per linear meter (W/m) for a fixed height [14].

$$P(\Delta\theta) = K\ \Delta\theta^{\mathrm{n}} \quad (2)$$

Since the aim of this study was to design an equation that would be valid for all heights and excess temperatures usually used for radiant baseboards in built environments, Eq. (2) needed to be generalized. According to norm EN 442 the heat emission from conventional radiators can also be estimated by Eq. (3) [22]. In this equation, q stands for heat output per meter length (=P/L), H for radiator height and a, b, c and d are polynomial coefficients. Also here, the coefficients are not universal and they apply for a certain radiator design only. As in case with Eq. (2), the values of the coefficients are determined by measurements and regression analysis.

$$q(H,\ \Delta\theta) = a\ H^{\mathrm{b}}\Delta\theta^{\mathrm{c \pm d \cdot H}} \quad (3)$$

In the present study, the form of Eq. (3) was used to design the aimed equation. The adaptation of Eq. (3) occurred in two steps. In the first step, the heat output data for baseboard heights 0.1, 0.15 and 0.2 m was extrapolated and interpolated linearly from the experimental data obtained for heights 0.13 and 0.185 m [18,19]. This was considered as acceptable since the baseboard heights of 0.1, 0.15 and 0.2 m are sufficiently close to the heights of 0.13 and 0.185 m, respectively. In the second step, values of coefficients in Eq. (3) for baseboard heights of 0.1–0.2 m and excess temperatures of 9–60 °C were determined using least squares method, as follows. First, the polynomial expression in Eq. (3) was linearized as shown by Eq. (4).

$$\ln(a) + b\ln(H_{\mathrm{k}}) + c\ln(\Delta\theta_{\mathrm{k}}) + d\,H_{\mathrm{k}}\ln(\Delta\theta) = \ln(q_{\mathrm{k}}),\ \text{where } k = 1,\ldots,55. \quad (4)$$

In a following step, the measured, extrapolated and interpolated heat output values (q_k) for the corresponding H_k and $\Delta\theta_k$ were substituted into Eq. (4). This resulted in a system of 55 equations. The generated equation system had the matrix form of $\mathbf{AX} = \mathbf{B}$, where $\mathbf{A}$ was a 55 × 4 matrix with rows [1, ln (H_k), ln ($\Delta\theta_k$), H_k ln ($\Delta\theta_k$)], $\mathbf{B}$ was a 55 × 1 column matrix with entries ln (q_k) and $\mathbf{X}$ was the column vector with elements to be determined. The elements of vector $\mathbf{X}$ are shown below.

$$\mathbf{X} = \begin{bmatrix} \ln(a) \\ b \\ c \\ d \end{bmatrix}$$

Generally, vector $\mathbf{X}$ is a least squares solution of the system $\mathbf{AX} = \mathbf{B}$ if and only if it is a solution of the associated normal system $\mathbf{A^T AX} = \mathbf{A^T B}$. As in our case $\mathbf{A^T A}$ (4 × 4) was invertible, the solution for $\mathbf{X}$ was thus obtained by Eq. (5).

$$\mathbf{X} = \left(\mathbf{A^T A}\right)^{-1}\mathbf{A^T B} \quad (5)$$

2.3. Statistical comparison

The calculated heat outputs obtained by the modified Eq. (3) were also statistically compared with the measured, extrapolated and interpolated values. For simplicity, these three types of values are in continuation collectively termed as reference values. In total, three equations have been used. Eqs. (6) and (7) were applied to quantify the absolute mean and maximum difference between the calculated and reference values, and Eq. (8) was used to calculate the Standard Error of Estimate (SEE) for the entire data set-up. The SEE is a standard statistical tool for rating the standard deviation of the residuals (differences). Ideally, the SEE = 0. In that case there would be no difference between the reference and calculated values. However, in reality, this is never the case. Therefore, in practice, the goal is always to minimize the SEE.

Table 2
The geometries of a single waterway of the tested radiant baseboards, together with flow parameters. The calculations were performed at a mean water temperature of 50 °C.

Item	$\dot{m}$(g/s)	h (mm)	w (mm)	d_{eq} (mm)	v (m/s)	$Re_{d_{eq}}$	ε/d_{eq}	f	$\Delta p/L$ (Pa/m)
I	10.6	20	15	17.4	0.05	$1.43 \cdot 10^3$	$8.6 \cdot 10^{-5}$	0.045	3
II	56.0	20	15	17.4	0.24	$7.53 \cdot 10^3$	$8.6 \cdot 10^{-5}$	0.033	54
III	112.5	20	15	17.4	0.48	$1.51 \cdot 10^4$	$8.6 \cdot 10^{-5}$	0.028	180

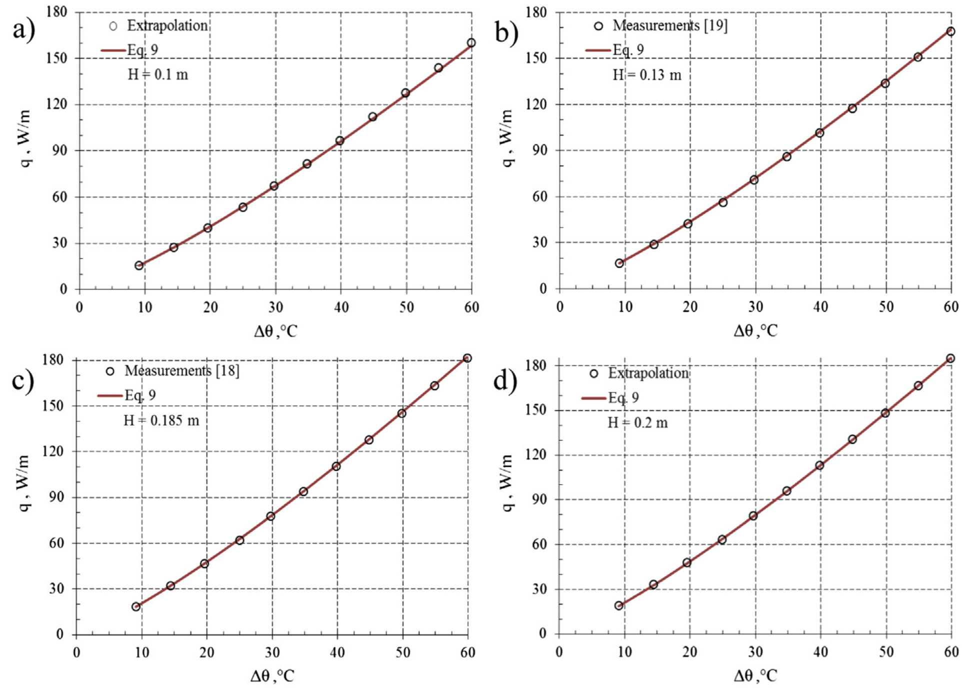

Fig. 3. a–3d. Comparative plots of the measured, extrapolated and calculated heat outputs by Eq. (9). a) shows the plot for a baseboard height of $H = 0.1$ m, b) for $H = 0.13$ m, c) for $H = 0.185$ m and d) for $H = 0.2$ m. The range of excess temperatures was the same for all four cases, i.e. $\Delta\theta = 9–60$ °C.

$$\Delta_{ave} = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|q_{calc,\ i} - q_{ref,\ i}\right|}{q_{calc,\ i}} \tag{6}$$

$$\Delta_{max} = \max\left(\frac{\left|q_{calc,\ i} - q_{ref,i}\right|}{q_{calc,\ i}}\right) \tag{7}$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}\left(q_{ref,\ i} - q_{calc,\ i}\right)^2}{n}} \tag{8}$$

3. Results

In general, the best curve fit in the least squares sense is obtained by minimizing the sum of squared differences between the reference and the calculated (fitted) values. Practically this means that in the present study the values of the elements in vector **X** were determined so that the absolute differences between the reference and the calculated values were the smallest possible. The obtained values for elements in vector **X**, applying the conditions and the calculation steps described at the end of Section 2.2, are presented below.

$$\mathbf{X} = \begin{bmatrix} 0.747 \\ 0.313 \\ 1.246 \\ -0.147 \end{bmatrix}$$

Accordingly, $\ln(a) = 0.747 \Leftrightarrow a = 2.110$, $b = 0.313$, $c = 1.246$ and $d = -0.147$ are the values of the constant and exponents for Eq. (3), respectively. Finally, the final form of the modified Eq. (3) is shown by Eq. (9).

$$q(H,\ \Delta\theta) = 2.110\cdot H^{0.313}\cdot\Delta\theta^{1.246-0.147\cdot H} \tag{9}$$

The comparative plots between the reference values and those calculated by Eq. (9) are demonstrated in Fig. 3a–d. The rings represent the reference values and the solid lines show the calculated values. The plots confirm that the proposed Eq. (9) is applicable for all baseboard heights from 0.1 to 0.2 m and excess temperatures from 9 to 60 °C. In that height and temperature range, the mean and maximum absolute differences between the reference and calculated values were less than 0.8 and 1.6%, respectively (Table 3). The dispersion (SEE) between the values for $\Delta\theta = 9–60$ °C and $H = 0.1$ m was 1.09 W/m, and ≤ 0.65 W/m for $H = 0.13–0.2$ m. It should be noted that dispersion for $H = 0.1$ m and $\Delta\theta = 9–46.6$ °C was also ≤ 0.65 W/m. Practically this means that for supply water temperatures between 35 and 71.5 °C and baseboard heights between 0.1 and 0.2 m, the maximum uncertainty of the prediction by Eq. (9) is ± 0.65 W/m.

Furthermore in Fig. 4a, the increase of relative heat output for five different baseboard heights between 0.1 and 0.2 m is shown. It can be observed that heat emission on average increases by approximately 2.1% per centimeter of height. The increase for heights between 0.1 and 0.15 m is somewhat higher than average, i.e. around 2.25%/cm, and for heights 0.15–0.2 m it is slightly lower than average, about 2.0%/cm. The increase for $H = 0.1–0.15$ m and $\Delta\theta = 9–60$ °C is also approximately linear and constant, while between $H = 0.15$ m and $H = 0.2$ m the increase is exponential. In

Table 3
Overview of the absolute mean and maximum differences and SEE between the reference and values calculated by Eq. (9) for $\Delta\theta = 9–60$ °C.

Item	H (mm)	Δ_{ave} (%)	Δ_{max} (%)	SEE (W/m)
I	100	0.78	1.35	1.09
II	130	0.78	1.21	0.64
III	185	0.32	0.72	0.42
IV	200	0.57	1.60	0.35

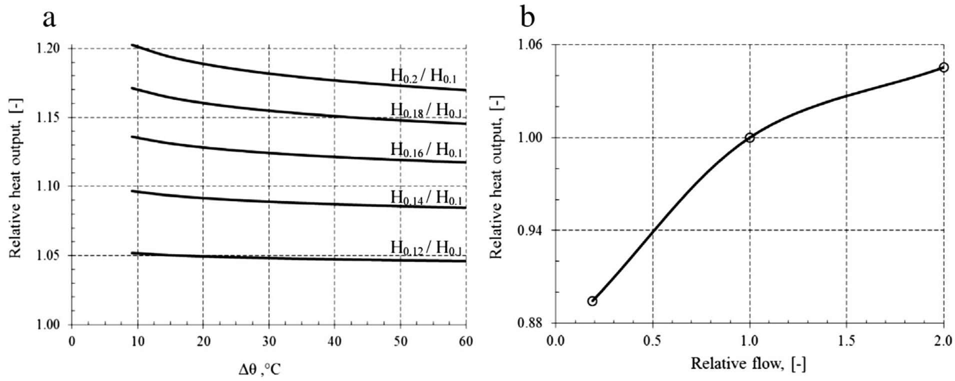

Fig. 4. a. The increase of relative heat output as a function of excess temperature for five baseboard heights between 0.1 and 0.2 m. b. The measured relation between the relative heat output and relative water flow [18,19].

particular for the range $\Delta\theta = 9–20$ °C, or more precisely for supply water temperatures 35–45 °C. Therefore, if radiant baseboards are to be operated at water supply temperatures lower than 45 °C their height should be the maximum possible in order to maximize the thermal output of the system.

Moreover, according to measurements the heat outputs at a water flow of 112.5 g/s were on average 4.5% higher than the outputs at 56.0 g/s, which were about 10.5% higher than the outputs at 10.6 g/s [18,19]. This finding is also illustrated in Fig. 4b. In other words, a doubling of the water flow through the radiant baseboards would increase their total heat output by about 4.5%. On the other hand, the pressure loss on the water-side generated by the doubling of the flow would increase by approximately 230% (Table 2). This means that for the case considered, the hydraulic power loss due to increased water flow would be roughly 6.4 times higher than the heat power gain due to increased heat emission. This relation between power loss and gain is not universal and applies for a certain baseboard design at certain water flows only. However, this gives an indication of at which water flow rates radiant baseboards should be operated.

4. Discussion

Despite their potential and flexibility, the use of radiant baseboards for space heating in Sweden is still very limited. Besides, until now the linear heat outputs from radiant baseboards were predicted by expressions valid for a certain baseboard height. As this heating system may play an important role for space heating in the future, this limitation needed to be addressed. The main aim of the present study was therefore to design a reliable equation for prediction of linear heat output for baseboard heights between 0.1 and 0.2 m and excess temperatures in range of 9–60 °C. For this purpose, the recently reported measurements performed in the United Kingdom's leading independent laboratory (BSRIA) were used [18,19]. The proposed equation (Eq. (9)) is an adaptation of the expression given by the European norm EN 442, and is a function of both baseboard height and excess temperature. It was shown that the predictions of linear heat outputs by the proposed equation were in close agreement with experimental data obtained in the laboratory.

The laboratory measurements also revealed that doubling the water flow through the radiant baseboards will only slightly increase the heat emission. It is therefore recommended to use the current guideline value of 100 Pa/m for water-side pressure loss for system design, for two reasons. Firstly, to keep the energy usage for pumping at a moderate level and secondly to ensure an acceptable temperature drop across each baseboard heating circuit.

As also confirmed in this study, the basic advantage of the radiant baseboards lies in their placement along the bottom of the room walls. The room air in these parts of the heated space is usually the coldest. Therefore, the heat transfer ability of the radiant baseboards is much higher compared to other conventional radiator types. Since radiant baseboards are installed along the base of the walls, they are also suitable for homes without basements where cold floors are common [13]. In addition, due to their installation flexibility they can both operate as a sole heating system or be combined with already existing heating systems in the buildings. Due to this characteristic, the radiant baseboards might be an alternative when converting from electric to hydronic heating as well as for use in homes served by a heat pump. Other characteristics of the radiant baseboards are: I) elegant and discrete design, II) minimal interference with furniture placement, and III) the heat distribution near the floor.

The penultimate statement is ambivalent – since placing furniture close to baseboard heaters may degrade their heat output. In order to avoid this, a minimum of 150 mm of free space should be available in front of any baseboard heater [20]. The last characteristic creates a floor-to-ceiling temperature difference of about 1–2 °C, and thus produces a uniform temperature distribution across the entire heated space [15]. However, in the same study it was found that draught discomfort could occur at supply temperatures lower than 45 °C in a room with high glass surfaces.

Beside the operating water temperatures and the height, the heat emission from the radiant baseboards is strongly influenced by the free wall perimeter of the room. These room heaters should not therefore be installed in rooms with limited perimeter and high heating demand. A good practice guideline is that installed length of radiant baseboards per room should be around 12 m and not exceed 15 m. In this study it has been revealed that 12 m long and 0.185 m high radiant baseboards were able to give the same amount of heat as a 0.5 m high and 1.2 m long panel radiator of type 22. This means that radiant baseboards with this arrangement are able to replace most common radiator types used in built environments. However, it was also observed that a radiator of large dimensions and more compact design, such as type 33, was able to give more heat than the investigated radiant baseboards under the same conditions.

The proposed equation can easily be used and programed in energy simulation codes. In the future it would be interesting to simulate energy consumption for space heating in a given building served by radiant baseboards. This would further deepen the knowledge about advantages and limitations of this heating system. Another important subject remains to be explored. This is whether the heat emission from radiant baseboards can further be enhanced by an additional supply waterway (pipe), as a compliment to the existing one.

5. Conclusions

In this study the authors have investigated the thermal performance of hydronic radiant baseboards. The main goal was to design a reliable equation for prediction of heat output per unit length of the baseboard. Based on the obtained results the following can be concluded:

- The heat outputs predicted by the proposed equation (Eq. (9)) were in close agreement with the previous experimental investigation. Therefore the proposed equations can be used with confidence for system design in practice.
- A doubling of the water flow through the investigated baseboards would increase the total heat emission by only 4.5%. It was therefore recommended to use the current guideline value of 100 Pa/m for water-side pressure loss for the system design.
- Calculations showed that heat emission per unit length from radiant baseboards increased by approximately 2.1% per centimeter of height. It is therefore suggested to use radiant baseboards of maximum possible height if this heating system is to be operated at supply water temperatures below 45 °C.
- Because of their installation flexibility and discreet finish, radiant baseboards can be used both in new-built and in retrofitted buildings. Either as the sole or as an additional heat-distributing system.
- Radiant baseboards should not be used in rooms with small wall perimeter and high heating demand.

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