Verification and Improving the Heat Transfer Model in Radiators in the Wide Change Operating Parameters

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Abstract: Laboratory measurements and analyses conducted in a wide range of changes of water temperature and mass flow rate for different types of radiators allowed to provide limitations and assessment of the current radiators heat transfer model according to EN 442. The inaccuracy to determine the radiator heat output according to EN 442, in case of low water mass flow rates may achieve up to 22.3% A revised New Extended Heat Transfer Model in Radiators NEHTMiRMd is general and suitable for different types of radiators both new radiators and radiators existing after a certain period of operation is presented. The NEHTMiRMd with very high accuracy describes the heat transfer processes not only in the nominal conditions—in which the radiators are designed, but what is particularly important also in operating conditions when the radiators water mass flow differ significantly from the nominal value and at the same time the supply temperature changes in the whole range radiators operating during the heating season. In order to prove that the presented new model NEHTMiRMd is general, the article presents numerous calculation examples for various types of radiators currently used. Achieved the high compatibility of the results of the simulation calculations with the measurement results for different types of radiators: iron elements (not ribbed), plate radiators (medium degree ribbed), convectors (high degree ribbed) in a very wide range of changes in the water mass flow rates and the supply temperature indicates that a verified NEHTMiRMd can also be used in designing and simulating calculations of the central heating installations, for the rational conversion of existing installations and district heating systems into low temperature energy efficient systems as well as to directly determine the actual energy efficiency, also to improve the indications of the heat cost allocators. In addition, it may form the basis for the future modification of the European Standards for radiator testing.

Keywords: radiator heat transfer; radiator efficiency; mass flow rate change; radiator temperature profile; radiator mean temperature

1. Introduction

Studies and analyses have shown that obtaining up to a good operating thermal characteristics of the radiators currently tested according to the “EN442-2 Radiators. Thermal power and test methods” is not possible. Analyses of the conducted measurement results have shown that the current description of the heat transfer process in convective radiator according to EN 442 [1,2] equation is practically correct only for radiators with a low degree of ribbing and mass flow rate close to the nominal value. In the case of smaller radiators mass flows, according to conducted analysis, the discrepancies are up to a dozen percent depending on the type of radiators and the water mass flow rate. The need to correctly determine the influence of the water mass flow on the heat output of the radiators was felt and signalled in some way, and various attempts were made to solve this problem. For example, Calisir et al. [3], for various connection configurations of the tested radiators, provided formulas determining the radiator heat output depending on the mass flow rate and the temperature difference of the supply and return water the form of exponential
equations. After the measurements in accordance with EN 442-2 [2], the general formula for the radiator heat output was given in the form:

\[ \Phi = K_T \cdot \Delta T_w^m \cdot q_m^c \]  

(1)

where:

- \( K_T \), \( m \) — radiator constants based on the test results.
- \( \Delta T_w \) — water temperature drop in the radiator

For example, for the TBSE (Top-Bottom-Same-Ends) radiator connection system

\[ \Phi_I = 4064.9 \cdot \Delta T_w^{1.033} \cdot q_m^{1.014} \]  

(2)

for the TBOE (Top-Bottom-Opposite-Ends) radiator connection system

\[ \Phi_{II} = 3456.0 \cdot \Delta T_w^{0.997} \cdot q_m^{0.955} \]  

(3)

When it is well known from the “Physics Laws” that if the water temperature drops in the radiator \( \Delta T_w \) and the radiator mass flow rate \( q_m \) are known—the radiator heat output is determined only by the equation:

\[ \Phi_I = q_m \cdot c_p \cdot \Delta T_w \]  

(4)

The comparison of the radiator heat output in the TBSE system obtained from the formula above and according to the “Laws of Physics” in this case is shown in Figure 1.

![Figure 1](image.png)

Figure 1. The discrepancy between the actual radiator power heat output and calculated according to the equation for the TBOE system.

Some researchers try to attribute the influence of heat transfer conditions in the radiator from the water side only to the phenomenon of convection from the heated room side—which leads to mathematically correct relationships to a very limited extent, but at the same time contradicting the source research of this phenomenon carried out by Nusselt [4].

According to pioneering research performed by Nusselt on the of the heat transfer process in the free convection conditions the exponent of the power taking into account the influence of the temperature difference between the wall and the surrounding air in the case of laminar air flows does not exceed the value 0.25 while in the conditions of turbulent air flows it does not exceed the value 0.33.

For example, A. B. Erdoğmus [5] in order to obtain acceptable accuracy for the various types of radiators tested with different water mass flow rate, suggested the following dependence for the radiator 1-row type:

\[ \Phi_I = 2.795 \cdot 

\[ \Delta T_w^{1.4115} \]  

(5)

for the radiator 3-row type:

\[ \Phi_I = 7.908 \cdot 

\[ \Delta T_w^{1.3846} \]  

(6)
Assessing the results from the “mathematical” point of view, they may seem correct, but looking from the physical side of the convection phenomenon, we cannot forget about the pioneering source studies by Nusselt [4]—that in convection conditions the exponent “m” must not exceed the value of 1.33.

In the publication [6] by Marchesi, R., at al., it was emphasized that the actual operating conditions of the radiators differ significantly from the conditions in the chamber test according to EN 442, among others—curtains, water mass flow rate, supply temperature and the connection method of the radiator. After the tests, it was found that the radiators heat output decreased to 15% due to hydraulic connections and due to changes in the water mass flow from 10% to 20%. It should be clearly stated that according to the regulations of the currently binding [2] EN 442 standard, it is not possible to determine in accordance with the “Physics Laws”, neither the actual thermal performance nor the energy efficiency of radiators. In principle, according to current practice, only the thermal heat output obtained by the radiator is tested in the assumed nominal and reconstructed design parameters in the radiator test chamber: water temperature drop in the radiator \( \Delta T_r = 20 \text{ K} \) or 10 K air temperature in the room \( t_i = +20 \text{ °C} \) and the difference between the average water temperature and the air temperature in the room \( \Delta T_w = 50 \text{ K} \). Even if at the request of the Manufacturers, tests were carried out on the heat output of radiators with a variable water mass flow \( q_m \)—the equations predicted for this case in the currently valid EN442-2 standard [2] led to results that are inconsistent with the “Physics Laws”. According to the proposed Equations (7)–(9) with a constant value of the exponent “c” it follows, that there is a continuous increase in the radiators heat output only due to the increasing of the water mass flow rate through the radiator \( q_m \).

In addition, it is very difficult to measure accurately the actual average temperature of the radiator—while measuring the temperature difference between the water supplying the radiator and the air temperature in the room—is indispensible and simple.

It is also known that the radiators will not work in heated rooms at the design air temperature equal to \( t_i = +20 \text{ °C} \), but at the operating air temperature which in case of using Individual billing for heating costs, may be for example \( t_i = +18 \text{ °C} \), while in case of oversized radiators and dysregulated central heating system or because of the individual thermal comfort requirements of the inhabitants may achieved \( t_i = +24 \text{ °C} \).

There is also a fundamental question about the physical and economic sense of obtaining and maintaining during the currently conducted approval tests of radiators—air temperature exactly equal to \( t_i = +20 \text{ °C} \) with acceptable small deviations while cooling the walls of the chamber and looking for such a radiator water mass flow rate with a yet unknown radiator thermal power to obtain the nominal radiator return water temperature—waiting for the stabilization of the heat transfer conditions, depending on the type of the tested radiator several dozen hours—when we know that obtained test results are useless in terms of the operation?

In addition at present a lot of emphasis is placed on activities related to the reduction of the air pollutant emissions e.g., by introducing high efficiency, low—temperature heating installations and low—temperature district heating systems—without changing the current standard EN 442 it will be very difficult to achieve.

Tests for the actual thermal characteristics of different types of radiators were carried out: iron 10-elements radiator, plate radiator, convector in different connection configurations and operating conditions—temperature and water mass flow rates generally changes from 20% to 200% of the nominal value. The iron elements TI-type radiator constitute the vast majority of the existing central heating installations in Poland. Of course, in currently designed central heating installations, plate radiators and convector radiators are most often used.

On the basis of the studies and analyses carried out the New Extended Heat Transfer Model in Radiators has been developed and verified. The \( NEHTMiR_{md} \) properly describes the heat transfer processes taking place in radiators used in heating systems over a wide range of operating conditions and not only under conditions close to the nominal.
This issue is particularly important in the case of existing buildings after their refurbished, where central heating installations with substantial oversized radiators and with too high supply temperature operate during the heating season practically at a mass flow rate of 2 times to 4 times smaller than the nominal value [7,8].

Conducted analyses of the actual heat consumption in more than 600 refurbished buildings showed that the vast majority did not achieve the expected reduction in actual heat consumption (and in some cases actual consumption increased) [7], due to improperly operating conditions of radiators with very high supply temperature, low mass flow rate and the associated low energy efficiency of the heating systems (Most of which use the Iron Element Radiator TI-type).

In such facilities there is an urgent need to develop “Individual projects” for the thermal and hydraulic adaptation of existing oversized central heating systems to new actual heat demand of the rooms, which is not possible without knowledge of a good model describing the heat transfer in radiators under these conditions.

In addition in such buildings the individual heat cost allocator is commonly used and the current heat transfer model in radiators according to EN 442 [2] is used for their software. As the measurements and analyses carried out have shown, errors due to differing significantly from the nominal of the radiators and the incorrect installation point the heat allocators reach up to 40%.

The developed NEHTMiR md model is essential for: directly assessing the actual energy efficiency of the heating system in the heating season and in the Individual Heating Costs Allocation System, while established the suitable conditions for operational regulation of the Central heating installations and district heating systems.

In addition it will also allow for an appropriate modification of the EU Standards regarding the scope and test conditions of the radiators.

2. Description of the Existing State

Currently to determine the thermal characteristics of a convector and radiators of different types the EN 442 [2] is commonly used. The general equation describing the radiators heat output according to the EN 442 [2] standard is in the form of:

\[ \Phi_I = K_T \cdot L^a \cdot H^b \cdot \Delta T^c_0 + c_1 \cdot q_m \]  
(7)

where:

\[ c_o, c_1, K_T, a, b, c \]

radiator constants based on the tests

\[ \Delta T — \text{arithmetic mean temperature difference, [K]} \]

\[ \Phi_I — \text{radiator heat output, [W]} \]

\[ L — \text{radiator length, [m]} \]

\[ H — \text{radiator height, [m]} \]

\[ q_m — \text{water mass flow, [kg/s]} \]

In the case that the Manufacturer requests testing of radiators of varying length and fixed height, with a variable water mass flux, the equation describing the radiators thermal power shall take the form of:

\[ \Phi_I = K_T \cdot L^a \cdot H^b \cdot \Delta T^c_0 \cdot q_m^c \]  
(8)

On the other hand, when conducting tests on radiators of varying height and fixed length with a variable water mass flux equations in the form of:

\[ \Phi_I = K_T \cdot L^a \cdot H^b \cdot \Delta T^c_0 + c_1 \cdot q_m^c \]  
(9)

It should be emphasized that at present there is practically nothing tested on the dependence of the radiator’s heat power output on the variable water mass flux. However.
all the above models do not properly describe the heat transfer process in the area of the radiators mass flows rates much smaller than the nominal values.

The problem of determining the actual radiators thermal characteristics under a wide changes of the water mass flow rate conditions is not a new issue. Pioneering research was carried out in the 1969 [9], 1970 [10] by W. Wasilewski and in the 1974 [11], 1981 [12] by R. Rabjasz in which he proposed an equation describing the radiators thermal output in the form of:

$$\Phi_I = q_m \cdot c_w \cdot \Delta t_1 \cdot [1 - (1 + m \cdot K_M \cdot \Delta t_m^m \cdot \frac{1}{q_m \cdot c_w})^{\frac{1}{m}}]$$  \hspace{1cm} (10)

where $c_w$ is the specific heat of the water, $m, K_M$—the constant thermal characteristics of the radiator, $\Delta t_1$—temperature difference between the supply water and the air temperature in the room.

3. NEHTMiR—New Extended Model of the Heat Transfer in Radiators

Studies and analyses have shown that the best current model of description of the heat transfer process in the radiators proposed by by W. Wasilewski [9,10] and by R. Rabjasz [11,12] described by the Equation (10) is correct for water flows through the radiators not less than around 40% of the nominal value. Below these mass water flow values differences between actual and calculated radiator heat output are unacceptable and the problem is bigger in the case of ribbed radiators with larger quotient of the outer surface transmitting heat to the air in the room and the surface contacting the water.

The main assumption in the verified New Extended Heat Transfer Model in Radiators NEHTMiR is the variability of the radiator heat transfer coefficient depending on the water mass flow rate and temperature difference described in the equation:

$$u_x = K_{M1} \cdot \Delta T_x^m \cdot q_m^{lm}$$ \hspace{1cm} (11)

In operating conditions the heat transfer process in radiators takes place at a variable value of the heat transfer coefficient due to temperature and water mass flow rate changes described by Equation (11). The New Extended Heat Transfer Model in Radiators, NEHTMiR is presented in Figure 2.

For the elementary surface of the radiator $dA_x$ the heat flux transferring to the air in the room describes the equation:

$$dQ_{rx} = u_{rx} \cdot \Delta t_x \cdot dA_x$$ \hspace{1cm} (12)
Taking into account Equation (11) we will get:

\[ dQ_{rx} = K_{M1} \cdot \Delta t_{x}^{m+1} \cdot \frac{q_{m}^{dm}}{q_{m} \cdot c_{p}} \cdot dA_{x} \]  

(13)

An elementary change in the temperature difference between water and air along element dAx describes the equation:

\[ d(\Delta t_{x}) = -\frac{dQ_{rx}}{q_{m} \cdot c_{p}} \]  

(14)

On the basis of the above relationship substitute the Equation (13) we will receive:

\[ d(\Delta t_{x}) = -\frac{K_{M1} \cdot \Delta t_{x}^{m+1} \cdot dA_{x} \cdot q_{m}^{dm}}{q_{m} \cdot c_{p}} \]  

(15)

After conversion Equation (15) we will get:

\[ \frac{d(\Delta t_{x})}{\Delta t_{x}^{m} + 1} = -\frac{K_{M1} \cdot dA_{x} \cdot q_{m}^{dm}}{q_{m} \cdot c_{p}} \]  

(16)

Integrating in the boundaries for: \( Ax = 0, \Delta t_{x} = \Delta t_{1} \) and for \( Ax = Ar, \Delta t_{x} = \Delta t_{2} \)

\[ \int_{\Delta t_{1}}^{\Delta t_{2}} \frac{d(\Delta t_{x})}{\Delta t_{x}^{m} + 1} = \int_{0}^{Ar} -\frac{K_{M1} \cdot dA_{x}}{q_{m} \cdot c_{p}} \]  

(17)

after the transformation we will get the equation describing the energy efficiency of the radiators in the form of:

\[ EF_{rmd} = [1 - (1 + m \cdot K_{M1} \cdot \Delta t_{1}^{m} \cdot Ar \cdot \frac{1}{q_{m}^{dm} \cdot c_{w}})^{-\frac{1}{m}}] \]  

(18)

and radiator heat output:

\[ Q_{r} = EF_{rmd} \cdot q_{m} \cdot (t_{s} - t_{t}) \cdot c_{w} \]  

(19)

Equation describing the temperature of the return water from the radiator:

\[ t_{r} = t_{s} - \Delta t_{1} \cdot [1 - (1 + m \cdot K_{M1} \cdot \Delta t_{1}^{m} \cdot Ar \cdot \frac{1}{q_{m}^{dm} \cdot c_{w}})^{-\frac{1}{m}}] \]  

(20)

The exponent \( dm \) is variable and its value depends on the radiator water mass flow rate and the radiator type. In the case of the plate, multi-row radiator with a ribbing level up to \( \phi = 8.0 \) good result can be achieved using Equation (21):

\[ dm = C_{1} \cdot \ln(q_{m}) + C_{2} \]  

(21)

For the convectors with a higher degree of ribbing, especially in forced airflow conditions, a better result can be achieved by describing the exponent \( dm \) as a power function in the form of Equation (22):

\[ dm = D_{1} \cdot q_{m}^{D_{2}} \]  

(22)

Generally, in the case of radiators optimization of the temperature distribution on the surface of the heater in terms of obtaining the greatest possible radiator heat output—it is important but solved only once at the stage of construction (design) of the radiator. However, during the operation—only the actual thermal characteristics of the radiator used are important. That means, how the actual radiator heat output is changing at the set temperature of the air in the heated room—when changing the parameters over which we are influenced i.e., the supply temperature \( t_{s} \) and the radiator water mass flow \( q_{m} \). And also whether the radiator heat output corresponds to the actual thermal needs of the room.
During the radiators thermal characteristics tests the actual energy efficiency can be directly determined in a very wide range of parameter changes by measuring for the specified water mass flow rates $q_m$ and the set supply temperature $t_s$ and air in room $t_i$—two standard radiator response parameters: the heat output $Q_r$ and return water temperature $t_r$.

$$EF_{md} = \frac{(t_s - t_r)}{(t_s - t_i)}$$  \hspace{1cm} (23)

### 4. Purpose and Scope of the Studies Carried Out

The primary purpose of the studies was to verify the developed New Extended Heat Transfer Model in Radiators NEHTMiR$_{md}$ and also experimentally verify the relationship between the indications of heat cost allocators located at different heights on the radiator and the measured actual amount of heat transferred by the radiator to the environment.

**Test Methodology**

The research used a closed-type chamber located in the Accredited C.O. Armature Laboratory of the Institute of Heating and Sanitary Technology in Radom and the open-type chamber located in the Heating and Air Conditioning Institute of the Warsaw University of Technology.

The temperature and water mass flow rate measurements were automatically taken every 10 s and recorded using the AL 154 DAO system. Temperature measurements were made using a multi-channel temperature measurement system. The system ensures the accuracy of the temperature measurement at 0.1 K and the automatic recording of measurement values. And the thermographic camera AGA 750 and AGEMA 470 Pro with digital thermographic image recording system for recording and processing thermal images was used to determine the actual temperature distribution on the surface of the radiator and chamber walls and determine the emissivity of the surface of walls and radiator on the basis of a known measured temperature. The instruments and measuring systems used were checked and periodically checked prior to the start of the tests.

During the tests it was measured: the temperature of the water supply $t_s$, return $t_r$, air temperature in room $t_i$ at the reference point at height of (0.75 m from the floor at a distance of 1.5 m from the heater), the temperature on the surface of the radiator at 8 points, the temperature on the mounting plate of the heat cost allocators and the water mass flow rates $q_m$.

In order to ensure high accuracy of the measurement water mass flow rates $q_m$, especially at the lowest flows, it was carried out from time to time the check measurements by weight method. An additionally three programmed heat cost allocators located at a height of 0.5 h, 0.52 h and at the height currently commonly used by Heat Cost Allocation Companies 0.75 h have been installed on radiator.

According to thermography measurements, an example of a temperature distribution on the surface of heater T1 is shown on Figure 3.

The location of the heat cost allocators and the arrangement of the radiator temperature measuring points are shown in the Figure 4.
The study was conducted over several weeks in a wide range of changes in the temperature and the radiator mass flow rates.

Throughout the test period:
- temperature of the radiator supply water changed from 37.7 °C to 68.8 °C, the average value 51.2 °C.
- temperature of return from the radiator changed from 25.6 °C to 60.8 °C, the average value 40.0 °C.
- the radiator water mass flow varies from 0.0036 kg/s, 29.6% (nominal value) to 0.0256 kg/s, 212.1% (nominal value)—the average water mass flow 0.0121 kg/s
- the radiator heat output varies from 122.9 W to 788.6 W—the average heat output 409.0 W.

Graphically the cumulative range of parameter changes such as: $t_s$, $t_r$, $t_i$, $q_m$, during the studies are shown in the following drawings in the Figures 5–9.
Figure 5. Measuring series I.

Measuring series II.

Figure 6. Measuring series II.

Measuring series III.
Figure 7. Measuring series III.

Figure 8. Measuring series IV.

Figure 9. Measuring series V.
An additional range of quantitatively managed tests to determine the actual operational thermal characteristics of the T1 10-elements iron radiator is shown graphically in Figure 10.

- temperature of the radiator supply water $70.2 \degree C \pm 0.4 \, K$,
- return temperature from the radiator changed from $35.3 \degree C$ to $63.4 \degree C$,
- the radiator water mass flow varies changed from 0.0034 kg/s (39.0% nominal value) to 0.031 kg/s (356.0% nominal value)
- the radiator heat output varies from 481 W to 924 W.

5. Result and Analysis

The comparison between the measurement and simulation calculations result of radiator heat output, radiator efficiency and return water temperature according to the
NEHTMiR\textsuperscript{md} for 10-elements iron radiator T1 with no extended external surface (ribbed degree around 1.0) at \(t_s = 70.0\, ^\circ\text{C}\) is presented in the Tables 1 and 2.

Table 1. The comparison between the measurement and the calculations results Radiator T1. \(t_s = 70.0\, ^\circ\text{C}\).

| No. | \(t_s\) | \(t_r\) | \(t_i\) | \(\text{qm}\) | \(\text{Qr ac}\) | \(\text{Qr EN}\) | \(\text{dQr EN}\) | \(\text{Qr md}\) | \(\text{dQr md}\) | \(\text{qmx/qmo}\) |
|-----|--------|--------|--------|------------|----------------|----------------|----------------|----------------|----------------|--------------|
| 1   | 70.6   | 63.4   | 21.1   | 0.0307     | 924            | 913            | 1.2            | 911            | 1.3            | 3.56         |
| 2   | 70.6   | 57.8   | 20.9   | 0.0155     | 832            | 847            | 1.8            | 837            | \(-0.6\)       | 1.79         |
| 3   | 70.5   | 50.1   | 20.7   | 0.0086     | 737            | 756            | 2.6            | 733            | 0.5            | 1.00         |
| 4   | 69.7   | 42.2   | 20.3   | 0.0051     | 588            | 662            | 12.7           | 602            | \(-2.5\)       | 0.59         |
| 5   | 69.4   | 35.3   | 19.9   | 0.0034     | 481            | 588            | 22.3           | 491            | \(-2.2\)       | 0.39         |

Table 2. The comparison between the measurement and the calculations results Radiator T1. \(t_s = 70\, ^\circ\text{C}\).

| No. | \(t_s\) | \(t_r\) | \(t_i\) | \(\text{qm}\) | \(\text{EFr md}\) | \(\text{EFr ac}\) | \(\text{dEFr}\) | \(\text{tr md}\) | \(\text{dtr}\) | \(\text{Ts 0.75}\) | \(\text{qmx/qmo}\) |
|-----|--------|--------|--------|------------|----------------|----------------|------------|----------------|------------|----------------|--------------|
| 1   | 70.6   | 63.4   | 21.1   | 0.0307     | 924            | 0.1430         | 0.1450     | \(-1.3\)       | 63.5       | \(-1.3\)       | 66.1         | 3.56        |
| 2   | 70.6   | 57.8   | 20.9   | 0.0155     | 832            | 0.2601         | 0.2585     | 0.6            | 57.7       | 0.6            | 63.3         | 1.79        |
| 3   | 70.5   | 50.1   | 20.7   | 0.0086     | 737            | 0.4075         | 0.4097     | \(-0.5\)       | 50.2       | \(-0.5\)       | 60.3         | 1.00        |
| 4   | 69.7   | 42.2   | 20.3   | 0.0051     | 588            | 0.5709         | 0.5571     | 2.5            | 41.5       | 2.5            | 56.2         | 0.59        |
| 5   | 69.4   | 35.3   | 19.9   | 0.0034     | 481            | 0.7039         | 0.6885     | 2.2            | 34.6       | 2.2            | 50.4         | 0.39        |

Across a wide range of tests and measurements carried out, the discrepancy between the results obtained from simulation calculations based on the NEHTMiR\textsuperscript{md} and the actual values obtain from measurement’s had not exceed 2.5%.

On the other hand, using the EN 442 model, discrepancies in the radiator heat output under low water mass flow conditions reach up to \(-22.3\)%.

On Figures 11 and 12 for example a comparison between the result of the simulation calculations based on developed NEHTMiR\textsuperscript{md} and measurements the temperature distribution of the water flowing through the radiator and radiator surface temperature distribution along its height obtain from thermography measurements are provided (measurement 1 and 4).

![Figure 11](image-url)

**Figure 11.** Comparison of measurement and calculations results of water temperature, radiator surface temperature and radiator heat out distribution—measurement 1: \(t_s = 70.0\, ^\circ\text{C}, t_r = 63.4\, ^\circ\text{C}, t_i = 21.1\, ^\circ\text{C}, m_r = 0.0307\, \text{kg/s (m_{max})}\).
Figure 12. Comparison of measurement and calculations results of water temperature, radiator surface temperature and radiator heat out distribution—measurement 4: \( t_s = 69.7 \, ^\circ\text{C}, t_r = 42.2 \, ^\circ\text{C}, t_i = 20.3 \, ^\circ\text{C}, m_r = 0.0051 \, \text{kg/s (} m_{r_{\text{min}}}) \).

In the drawings above the radiator heat demand output means the heat transmitted to a given point at the height of the heater measured from the top. For example, if the water flow \( q_m = 0.0051 \, \text{kg/s}, \) measurement 4 and \( h_x = 0.6 \, \text{m}, Q_x = 602 \, \text{W} \)—heat output transferred by the entire radiator, if \( h_x = 0.3 \, \text{m}, Q_x = 381 \, \text{W} \)—heat output of the upper half of the radiator, if \( h_x = 0.4 \, \text{m}, Q_x = 467 \, \text{W} \)—heat output transferred by the upper \( \frac{3}{4} \) of the radiator surface.

For the entire range carried out of the measurement from 1 to 5 the result of simulation calculations according the \( \text{NEHTMiR}_{md} \) of the water and radiator surface temperature distribution along its height at \( t_s = 70.2 \, ^\circ\text{C} \) and mass flow rate \( q_{mx} \) from 39% to 356% of the nominal value are presented on Figures 13 and 14.

Figure 13. Profile of the radiator surface temperature temperature change, radiator T1. \( t_s = 70.2 \, ^\circ\text{C}, q_{mx} \) from 39% to 356% \( q_{mo} \) (nominal flow rate).
Profile of the radiator T1 surface temperature change, at \( t_s = 70.2 \, ^\circ\text{C} \), and mass flow rate \( q_{mx} \) from 39% to 356% nominal flow rate is presented in Figure 14.

![Figure 14](image)

**Figure 14.** Profile of the radiator surface temperature temperature change, radiator T1. \( t_s = 70.2 \, ^\circ\text{C} \), \( q_{mx} \) from 39% to 356% \( q_{mo} \) (nominal flow rate).

As it can be seen in Figure 13 under the high radiator water mass flow rate conditions, the profile of temperature changes and changes in radiator heat output along the heat transfer surface is close to linear. However, in the case of a small mass water flow rate (Figure 13—measurement 4)—the profile of the temperature distribution and radiator heat output changes are clearly different from the linear. In addition Figure 14 shows, that for a small water mass flow in the upper zone of the radiator there is the largest difference between the temperature of the water and the radiator wall of about 6.0 K. From the level less than half of the heater in this case, the temperature difference between the flowing water and the radiator wall \( T_f - T_s \) does not exceed 0.9 K.

Along the entire heat transfer area of the radiator the difference between the surface temperature determined from the thermography measurements and simulation calculations according to \( \text{NEHTMiR}_{md} \) for Elements Iron Radiator T1-type does not exceed 2%.

The developed \( \text{NEHTMiR}_{md} \) with high accuracy describes heat transfer processes under significant changes of the radiator water mass flow rate and temperature supply. It is highly recommended and useful for determination of seasonal operating conditions and actual energy efficiency of the radiators and the whole central heating installations.

On Figures 15 and 16 for example, the radiator T-1 surface temperature distribution according the thermography measurements at \( t_s = 89.7 \, ^\circ\text{C} \) and mass flow rate \( q_{mx} = 0.0307 \, \text{kg/s} \) and \( q_{mx} = 0.0051 \, \text{kg/s} \) are presented.
Figure 15. Radiator T1 surface temperature distribution according *thermography measurements*, measurements 1, flow $q_{\text{max}} = 0.0307$ kg/s ($q_{\text{max}}$)—356% nominal value.

Figure 16. Radiator T1 surface temperature distribution according *thermography measurements*, measurements 4, flow $q_{\text{mx}} = 0.0051$ kg/s—59% nominal value.

On Figures 17 and 18 the profile of the water and radiator T1 surface temperature change according simulation calculations by NEHTMiR for mass flow rate from 24% to 153% of the *nominal value* are presented.

Figure 17. *Iron Element Radiator T1 type*—water temperature distribution according *simulation calculations*, $t_s = 89.7$ °C, mass flow $q_{\text{mx}}$ from 24% to 153% nominal value.
The comparison between the measurement and simulation calculations result of radiator heat output, radiator efficiency and return water temperature according to the NEHTMiR_md for 2-row plate radiator Delonghi 22 with extended external surface (ribbed degree around 4.76) at $t_s = 89.8 \, ^\circ\text{C}$ and radiator water mass flow rate from 0.0059 kg/s, 24\% (nominal value) to 0.0379 kg/s, 153\% (nominal value) are presented in the Tables 3 and 4.

Table 3. The comparison between the measurement and the calculations results Radiator Delonghi 22, $t_s = 89.8 \, ^\circ\text{C}$.

| No. | $t_s$ | $t_r$ | $t_i$ | $q_m$ | Qr ac | Qr EN | dQr EN | Qr md | dQr md | Ts 0.75 | qmx/qmo |
|-----|------|------|------|------|------|------|-------|------|-------|--------|---------|
| 1   | 89.8 | 75.9 | 19.9 | 0.0379 | 2222 | 2277 | -2.46 | 2208 | 0.34  | 80.4   | 1.53    |
| 2   | 89.6 | 69.3 | 19.5 | 0.0247 | 2103 | 2135 | -1.52 | 2115 | -0.55 | 77.5   | 1.00    |
| 3   | 89.8 | 54.0 | 19.7 | 0.0120 | 1806 | 1779 | 1.46  | 1804 | 0.09  | 57.0   | 0.49    |
| 4   | 89.7 | 37.1 | 19.7 | 0.0059 | 1289 | 1407 | -9.16 | 1304 | -1.19 | 60.5   | 0.24    |

Table 4. The comparison between the measurement and the calculations results Radiator Delonghi 22, $t_s = 89.8 \, ^\circ\text{C}$.

| No. | $t_s$ | $t_r$ | $t_i$ | $q_m$ | Qr ac | EFr ac | EFr md | dEFr | tr md | dtr | Ts 0.75 | qmx/qmo |
|-----|------|------|------|------|------|--------|--------|------|-------|-----|--------|---------|
| 1   | 89.8 | 75.9 | 19.9 | 0.0379 | 2222 | 0.1989 | 0.1989 | -   | 75.9  | 0.0  | 80.4   | 1.53    |
| 2   | 89.6 | 69.3 | 19.5 | 0.0247 | 2103 | 0.2892 | 0.2915 | -0.8 | 69.2  | 0.2  | 77.5   | 1.00    |
| 3   | 89.8 | 54.0 | 19.7 | 0.0120 | 1806 | 0.5106 | 0.5108 | 0.0  | 54.0  | 0.0  | 57.0   | 0.49    |
| 4   | 89.7 | 37.1 | 19.7 | 0.0059 | 1289 | 0.7513 | 0.7602 | -1.2 | 36.5  | 1.7  | 60.5   | 0.24    |

Across a wide range of tests and measurements carried out for ribbed radiator Delonghi type 22, the discrepancy between the results obtained from simulation calculations based on the $\text{NEHTMiR}_{md}$ and the actual values obtain from measurement’s had not exceed 2.0\%.

On the other hand, using the EN 442 model, discrepancies in the radiator heat output under low water mass flow conditions reach up to $-9.2\%$.

On Figures 19 and 20 for example, the radiator Delonghi type 22, surface temperature distribution according the thermography measurements at $t_s = 89.6 \, ^\circ\text{C}$ and mass flow rate $q_{mx} = 0.0247 \, \text{kg/s}, (\text{measurement 2})$ and $q_{mx} = 0.0012 \, \text{kg/s}, (\text{measurement 3})$ are presented.
Figure 19. *Delonghi*-22 radiator—surface temperature distribution according thermography measurements, $t_s = 89.6 \, ^\circ\text{C}$, $t_r = 69.3 \, ^\circ\text{C}$, $t_i = 19.5 \, ^\circ\text{C}$, mass flow rate $q_m = 0.0247 \, \text{kg/s}$—measurement 2.

Figure 20. *Delonghi*-22 radiator—surface temperature distribution according thermography measurements, $t_s = 89.8 \, ^\circ\text{C}$, $t_r = 54.0 \, ^\circ\text{C}$, $t_i = 19.7 \, ^\circ\text{C}$, mass flow rate $q_m = 0.0120 \, \text{kg/s}$—measurement 3.

The comparison radiator Delonghi type 22 effectiveness according the tests and simulation calculations based on the NEHTMiR $\text{md}$ (measurements from 1 to 4) for radiator water mass flow rate from 22% to 100% of the nominal value are presented are presented on Figure 21.

The radiator Delonghi type 22, effectiveness according simulation calculations based on the NEHTMiR $\text{md}$ as a function of the radiator surface area for radiator water mass flow rate from 22% to 100% of the nominal value are presented on Figure 22.

The developed “New Extended Heat Transfer Model in Radiators” describes very well heat transfer processes under wide changes of the seasonal operating conditions also in the ribbed types of radiators.
Figure 21. Comparison of measurement and calculations results of the Delonghi-22 radiator effectiveness, measurement 1–4.

Figure 22. Delonghi-22, Radiator effectiveness as a function of radiator surface area.

On Figures 23 and 24 for example, comparison between the result of the simulation calculations based on developed NEHTMiR-md and measurements the temperature distribution of the water flowing through the radiator Delonghi type 22 and radiator surface temperature distribution along its height obtain from thermography measurements are provided (measurement 1 and 4).
Figure 23. Delonghi-22 comparison of measurement and calculations results of water temperature, radiator surface temperature and radiator heat out distribution—measurement 1, $t_s = 89.8 \, ^\circ\text{C}$, $t_r = 75.9 \, ^\circ\text{C}$, $t_i = 19.9 \, ^\circ\text{C}$, $q_{mx} = 0.0379 \, \text{kg/s}$, ($q_{m,\text{max}}$).

Along the entire heat transfer area of the radiator Delonghi-22, the differences between the actual temperature determined from the thermal measurements on the radiator Delonghi-22 surface and the results of the simulation calculations based on developed $\text{NEHTMiR}_{md}$ does not exceed 2.0%.

Figure 24. Delonghi-22 comparison of measurement and calculations results of water temperature, radiator surface temperature and radiator heat out distribution—measurement 4, $t_s = 89.7 \, ^\circ\text{C}$, $t_r = 37.1 \, ^\circ\text{C}$, $t_i = 19.7 \, ^\circ\text{C}$, $q_{mx} = 0.0059 \, \text{kg/s}$, ($q_{m,\text{min}}$).

The results of the simulation calculations based on the $\text{NEHTMiR}_{md}$ of the water and surface temperature profile for ribbed radiator Delonghi type 22, at water supply temperature $t_s = 90 \, ^\circ\text{C}$ and $t_i = 20 \, ^\circ\text{C}$ in the extended range of changes in the radiator water mass flow rate from 0.0009 kg/s (10% nominal value) to 0.0178 kg/s (203% nominal value) $q_{mo}$, are presented on Figures 25 and 26.
As can be seen on Figure 26, under conditions of high water mass flowing through the Delonghi-22 (ribbed degree 4.76), the profile of radiator temperature and heat output changes along the heat transfer surface is practically linear. In the case of a small mass water flow rate $q_{\text{min}} = 0.0059 \, \text{kg/s}$, 24% nominal $q_{\text{nom}}$, see Figure 24—measurement 4—the profile of temperature and radiator heat output changes are more non-linear compared to the non-ribbed radiator T1-type.

In order to carry out a complete verification of the New Extended Heat Transfer Model in Radiators, NEHTMiR-md an additional test cycle of convector type radiators with a very high degree of ribbing (from 22.1 to 36.9) also with forced airflow was carried out using a 3-steped drum fan.

The radiators were made up of 8 copper tubes diameter $18 \times 0.5 \, \text{mm}$, on which aluminum ribs of 0.15 mm thickness, diameter $125 \times 200 \, \text{mm}$, and spacing $5 \, \text{mm}$ were mounted. Tubes arranged in two rows in a combination 2 tubes of parallel or in a serial
connection. The convector radiator housing is made of steel sheet. The view of the convector radiators are showed on Figures 27 and 28.

![Figure 27. Convector Radiator-8RS, 8 tubes in series connection.](image)

![Figure 28. Convector Radiator-8RR, 8 tubes in parallel connection.](image)

A number of measuring series were carried out over a wide range of changes in the water mass flow rate through the convector radiators from approximately from 26% to 216% of the nominal mass flow rate.

The comparison between the measurement and simulation calculations result of radiator heat output, radiator efficiency and return water temperature according to the NEHTMiR_md for Convector Radiator type-8RR and type-8RS with extended external surface (ribbed degree around 22.1) at \( t_s = 51.1 \pm 0.1 \) °C and radiator water mass flow rate from 0.0047 kg/s (34% nominal) value to 0.0303 kg/s (216% nominal) value are presented in the Table 5.

**Table 5.** The comparison between the measurement results and the simulation calculations Convector Radiator type-8RR, \( t_s = 51.1 \) °C.

| No. | \( t_s \) | \( t_r \) | \( t_l \) | \( q_m \) | \( Q_{r ac} \) | \( Q_{r md} \) | \( dQ_{r md} \) | \( E_{Fr ac} \) | \( E_{Fr md} \) | \( dE_{Fr} \) | \( tr \) | \( dtr \) | \( q_{mx}/q_{mo} \) |
|-----|----------|----------|----------|--------|----------|----------|----------|--------|----------|----------|--------|--------|----------------|
| 1   | 51.2     | 46.6     | 21.0     | 0.0303 | 583      | 573      | 1.7      | 0.152  | 0.14944  | 1.7      | 46.7   | −0.2  | 2.16  |
| 2   | 51.1     | 36.9     | 21.0     | 0.0075 | 443      | 432      | 2.5      | 0.4702 | 0.45838  | 2.5      | 37.3   | −1.0  | 0.53  |
| 3   | 51.1     | 33.2     | 20.9     | 0.0053 | 396      | 379      | 4.3      | 0.5918 | 0.56656  | 4.3      | 34.0   | −2.3  | 0.38  |
| 4   | 51.0     | 33.3     | 21.0     | 0.0047 | 352      | 358      | −1.9     | 0.5907 | 0.60201  | −1.9     | 32.9   | 1.0   | 0.34  |

The comparison between the measurement and simulation calculations result of radiator heat output, radiator efficiency and return water temperature according to the NEHTMiR_md for Convector Radiator type-8RS with extended external surface (ribbed degree around 22.1) at \( t_s = 58.8 \pm 0.2 \) °C and radiator water mass flow rate from 0.0047 kg/s, 26% (nominal) value to 0.0303 kg/s 168% (nominal) value are presented in the Tables 6 and 7.
The comparison between the measurement results and the simulation calculations \textit{Convecter Radiator type-8RS}, $t_s = 58.9$ $^\circ$C.

| No. | $t_s$ | $t_r$ | $t_i$ | $qm$ | $Qr$ \text{ac} | $Qr$ \text{md} | $dQr$ \text{md} | $qmx/qmo$ |
|-----|------|------|------|------|-----------|-----------|-----------|----------|
| -   | $^\circ$C | $^\circ$C | $^\circ$C | kg/s | W | W | % | - |
| 1   | 58.6 | 32.1 | 21.0 | 0.0035 | 388 | 399.1 | -2.8 | 0.26 |
| 2   | 59.0 | 39.9 | 21.0 | 0.0064 | 511 | 531.9 | -4.1 | 0.47 |
| 3   | 59.0 | 46.9 | 20.9 | 0.0131 | 662 | 658.6 | 0.5 | 0.97 |
| 4   | 59.0 | 51.5 | 21.0 | 0.0226 | 709 | 720.9 | -1.7 | 1.68 |

The comparison between the measurement results and the simulation calculations \textit{Convecter Radiator type-8RS}, $t_s = 58.9$ $^\circ$C, Part 2.

| No. | $t_s$ | $t_r$ | $t_i$ | $qm$ | \text{EFr} \text{ac} | \text{EFr} \text{md} | \text{dEFr} | $tr$ \text{md} | $dtr$ | $qmx/qmo$ |
|-----|------|------|------|------|-----------|-----------|--------|-----------|--------|----------|
| -   | $^\circ$C | $^\circ$C | $^\circ$C | kg/s | - | - | % | $^\circ$C | % | - |
| 1   | 58.6 | 32.1 | 20.8 | 0.0035 | 0.7011 | 0.71998 | -2.7 | 31.4 | 2.2 | 0.26 |
| 2   | 59.0 | 39.9 | 21.4 | 0.0064 | 0.509 | 0.53006 | -4.1 | 39.1 | 2.0 | 0.47 |
| 3   | 59.0 | 46.9 | 21.7 | 0.0131 | 0.3236 | 0.32204 | 0.5 | 47.0 | -0.1 | 0.97 |
| 4   | 59.0 | 51.5 | 22.0 | 0.0226 | 0.2024 | 0.20584 | -1.7 | 51.4 | 0.2 | 1.68 |

The comparison between the measurement and simulation calculations result of the convector radiator type-8RR heat output, with extended external surface (ribbed degree around 22.1) according to the \textit{NEHTMiR} \text{md} at $t_s = 51.1$ $^\circ$C and radiator water mass flow rate from 0.0047 kg/s, 34\% (nominal) value to 0.0303 kg/s, 216\% (nominal) value are presented on the Figure 29.

![Figure 29. Comparison of the test and calculations results of the convection radiator type-8RR heat output change as a function of the mass flow rate, $t_s = 51.1$ $^\circ$C.](image)

The comparison between the measurement and simulation calculations result of the convector radiator type-8RS heat output, with extended external surface (ribbed degree around 22.1) according to the \textit{NEHTMiR} \text{md} at $t_s = 58.8 \pm 0.2$ $^\circ$C and radiator water mass flow rate from 0.0035 kg/s, 26\% (nominal) value to 0.0226 kg/s, 168\% (nominal) value are presented on the Figure 30.

The difference between the actual heat output of the convector radiators with extended external surface (ribbed degree around 22.1) and calculated according to the \textit{NEHTMiR} \text{md} do not exceed 4.3\%.
Figure 30. Comparison of test and calculations results of the convector radiator type-8RS heat output change as a function of the mass flow rate, $t_s = 58.9\, ^\circ C$.

6. Calculations Examples

6.1. Implementation of the “NEHTMiR”—Iron Elements Radiator T-1

Data input: $m = 0.27$, $Ar = 2.4\, m^2$, $K_M = 3.0$, $dm = 0.00$

The result of the measurement from 1 to 4 and simulation calculations of the Radiator T-1 effectiveness are presented on the Figure 31.

Figure 31. Radiator T-1, effectiveness according to the tests and simulations calculations by “NEHTMiRmd” in the mass flow range $m_r$ from 39% to 356% of the nominal value.

Example 1. $q_{nx} = 0.0307 \, kg/s$, $t_s = 70.6\, ^\circ C$, $t_i = 21.1\, ^\circ C$, $\Delta t_1 = 70.6 - 21.1 = 49.5\, K$ ($Q_{ac} = 924\, W$, $t_{rac} = 63.4\, ^\circ C$)

The radiator energy efficiency according $NEHTMiRmd$:

$EF_{rd} = \left[ 1 - (1 + 0.27 \times 3.0 \times 49.0^{0.27} \times 2.4 \times \frac{1}{0.0307 \times (1-0.00) \times cw})^{1/2} \right] = 0.143$

$EF_{ac} = \frac{(70.6-63.4)}{(70.6-21.1)} = 0.145$
Example 2. \( q_{mx} = 0.0155 \text{ kg/s} \), \( t_s = 70.6 \degree C \), \( t_i = 20.9 \degree C \), \( \Delta t_1 = 70.6 - 20.9 = 49.7 \text{ K} \) 
\( (Q_{ac} = 832 \text{ W}, t_{rac} = 57.8 \degree C) \)

The radiator energy efficiency according \( \text{NEHTMiR}_{md} \):

\[
EF_{md} = \left[ 1 - (1 + 0.27 \times 3.0 \times 49.7^{0.27} \times 2.4 \times \frac{1}{0.0155 (1-0.00) \times c_w})^{\frac{1}{1.3}} \right] = 0.260
\]

Actual radiator heat output:

\[ Q_{rac} = 832 \text{ W} \]

Heat output according to radiator effectiveness:

\[ Q_r = (70.6 - 20.9) \times 4186 \times 0.260 = 837 \text{ W} \]

Actual radiator heat output:

\[ Q_r = (70.6 - 20.9) \times 4186 \times 0.260 = 837 \text{ W} \]

Actual radiator return temperature \( t_{rac} = 57.8 \degree C \)

The return water temperature according to radiator effectiveness:

\[ t_{md} = 70.6 - 49.7 \times 0.260 = 57.7 \degree C, \Delta t_r = 0.00\%
\]

Example 3. \( q_{mx} = 0.0086 \text{ kg/s} \), \( t_s = 70.5 \degree C \), \( t_i = 20.7 \degree C \), \( \Delta t_1 = 70.5 - 20.7 = 49.8 \text{ K} \) 
\( (Q_{ac} = 737 \text{ W}, t_{rac} = 50.1 \degree C) \)

The radiator energy efficiency according \( \text{NEHTMiR}_{md} \):

\[
EF_{md} = \left[ 1 - (1 + 0.27 \times 3.0 \times 49.8^{0.27} \times 2.4 \times \frac{1}{0.0086 (1-0.00) \times c_w})^{\frac{1}{1.3}} \right] = 0.408
\]

Actual radiator heat output:

\[ Q_{rac} = 737 \text{ W} \]

Heat output according to radiator effectiveness:

\[ Q_r = (70.5 - 20.7) \times 4186 \times 0.408 = 733 \text{ W} \]

Actual radiator return temperature \( t_{rac} = 50.1 \degree C \)

The return water temperature according to radiator effectiveness:

\[ t_{md} = 70.6 - 49.8 \times 0.408 = 50.2 \degree C, \Delta t_r = 0.20\%
\]

Example 4. \( q_{mx} = 0.0051 \text{ kg/s} \), \( t_s = 69.7 \degree C \), \( t_i = 20.3 \degree C \), \( \Delta t_1 = 69.7 - 20.3 = 49.4 \text{ K} \) 
\( (Q_{ac} = 588 \text{ W}, t_{rac} = 42.2 \degree C) \)

The radiator energy efficiency according \( \text{NEHTMiR}_{md} \):

\[
EF_{md} = \left[ 1 - (1 + 0.27 \times 3.0 \times 49.4^{0.27} \times 2.4 \times \frac{1}{0.0051 (1-0.00) \times c_w})^{\frac{1}{1.3}} \right] = 0.571
\]

Actual radiator heat output:

\[ Q_{rac} = 588 \text{ W} \]

Heat output according to radiator effectiveness:

\[ Q_r = (69.7 - 20.3) \times 4186 \times 0.571 = 602 \text{ W} \]

Actual radiator return temperature \( t_{rac} = 42.2 \degree C \)

The return water temperature according to radiator effectiveness:

\[ t_{md} = 69.7 - 49.4 \times 0.571 = 41.5 \degree C, \Delta t_r = 2.5\%
\]

Example 5. \( q_{mx} = 0.0034 \text{ kg/s} \), \( t_s = 69.4 \degree C \), \( t_i = 19.9 \degree C \), \( \Delta t_1 = 69.4 - 19.9 = 49.5 \text{ K} \) 
\( (Q_{ac} = 481 \text{ W}, t_{rac} = 35.3 \degree C) \)

The radiator energy efficiency according \( \text{NEHTMiR}_{md} \):

\[
EF_{md} = \left[ 1 - (1 + 0.27 \times 3.0 \times 49.5^{0.27} \times 2.4 \times \frac{1}{0.0034 (1-0.00) \times c_w})^{\frac{1}{1.3}} \right] = 0.704
\]
\[ EF_{ac} = \frac{(69.4 - 35.3)}{(69.4 - 19.9)} = 0.690 \]

Actual radiator heat output:
\[ Q_{rac} = 481 \text{ W} \]
Heat output according to radiator effectiveness:
\[ Q_r = (69.4 - 19.9) \times 4186 \times 0.704 = 491 \text{ W}, \quad Q_{rac} = 481 \text{ W}, \quad dQr = 2.2\% \]
\[ t_{rac} = 35.3 \degree \text{C} \]

Actual radiator return temperature: \( t_{rac} = 35.3 \degree \text{C} \)

The return water temperature according to radiator effectiveness:
\[ t_{rmd} = 69.7 - 49.5 \times 0.704 = 34.6 \degree \text{C}, \quad dtr = 2.2\% \]

The Discrepancy

The discrepancy in the results of measurements and simulation calculations of the radiator efficiency, radiator heat output and return temperature in terms of mass flow rate changes from 39\% to 179\% of the radiator nominal mass flow rate does not exceed 2.5\%.

6.2. Implementation of the “NEHTMiR” for 2-Row Delonghi-22 Ribbed Radiator

Data input:
\[ m = 0.32, \quad Ar = 8.37 \text{ m}^2, \quad K_M = 0.137, \quad \varphi = 4.3, \quad D_1 = 0.0199, \quad D_2 = -0.0721 \]

The result of the measurement from 1 to 5 and simulation calculations of the Radiator Delonghi-22 effectiveness are presented on the Figure 32.

![Figure 32](image)

**Figure 32.** Radiator Delonghi-type 22—effectiveness according to the tests and simulations calculations by “NEHTMiR\_md” in the mass flow range \( m_r \) from 20\% to 150\% of the nominal value.

**Example 6.** \( q_{mix} = 0.0379 \text{ kg/s}, \quad t_s = 89.8 \degree \text{C}, \quad t_i = 19.9 \degree \text{C}, \quad \Delta t_1 = 89.8 - 19.9 = 69.9 \text{ K}, \quad D_1 = 0.0199, \quad D_2 = -0.0721. \) (\( Q_{ac} = 2215 \text{ W}, \quad t_{rac} = 75.9 \degree \text{C} \))

The radiator energy efficiency according “NEHTMiR\_md”:
\[ d_m = 0.0199 \times \ln(0.0379) - 0.0721 = 0.00025 \]
\[ EF_{rmd} = [1 - (1 + 0.32 \times 8.37 \times 69.9^{0.32} \times 2.4 \times \frac{1}{0.0379(1 - 0.00025 \times c_w)})^{1/2}] = 0.199 \]
\[ EF_{ac} = \frac{(89.9 - 75.9)}{(89.9 - 19.9)} = 0.199 \]

Actual radiator heat output:
\[ Q_{rac} = 2221 \text{ W} \]
Heat output according to radiator effectiveness:
\[ Q_r = (89.9 - 19.9) \times 4186 \times 0.199 = 2208 \text{ W}, \quad Q_{rac} = 2221 \text{ W}, \quad dQr = 0.34\% \]
Actual radiator return temperature: \( t_{rac} = 75.93 \degree \text{C} \).
The return water temperature according to radiator effectiveness:
\[ t_{rdm} = 89.97 - 69.9 \times 0.1889 = 75.9 \, ^\circ C, \, dtr = 0.0\% \]

**Example 7.** \( q_{mx} = 0.0247 \, kg/s, \, t_s = 89.6 \, ^\circ C, \, t_i = 19.5 \, ^\circ C, \, \Delta t_1 = 89.6 - 19.5 = 70.1 \, K, \)
\[ D_1 = 0.0199, \, D_2 = -0.0721. \) \( (Q_{ac} = 2103 \, W, \, t_{rac} = 69.3 \, ^\circ C) \)

The radiator energy efficiency according “NEHTMiR\(_{md}\)”:
\[ d_m = 0.0199 \times \ln(0.0247) - 0.0721 = 0.008275 \]
\[ EF_{rdm} = \left[ 1 - \left( 1 + 0.32 \times 8.37 \times 70.1^{0.32} \times 2.4 \times \frac{1}{0.0247(1+0.008275) \times c_p)} \right)^{\frac{1}{0.32}} \right] = 0.2915 \]
\[ EF_{ac} = \left( \frac{89.6 - 69.3}{89.6 - 19.5} \right) = 0.2892 \]
Actual radiator heat output according to “NEHTMiR\(_{md}\)”:
\[ Q_{rac} = 2103 \, W \]
Heat output according to radiator effectiveness:
\[ Q_r = (89.6 - 19.5) \times 4186 \times 0.2915 = 2115 \, W, \, Q_{rac} = 2103 \, W, \, dQ_r = 0.55\% \]
Actual radiator return temperature: \( t_{rac} = 69.3 \, ^\circ C \)
The radiator return temperature according the “NEHTMiR\(_{md}\)” radiator effectiveness:
\[ t_{rdm} = 89.6 - 70.1 \times 0.2915 = 69.2 \, ^\circ C, \, dtr = 0.2\% \]

**Example 8.** \( q_{mx} = 0.0120 \, kg/s, \, t_s = 89.8 \, ^\circ C, \, t_i = 19.7 \, ^\circ C, \, \Delta t_1 = 89.8 - 19.5 = 70.1 \, K, \)
\[ D_1 = 0.0199, \, D_2 = -0.0721. \) \( (Q_{ac} = 2103 \, W, \, t_{rac} = 69.3 \, ^\circ C) \)

The radiator energy efficiency according “NEHTMiR\(_{md}\)”:
\[ d_m = 0.0199 \times \ln(0.0120) - 0.0721 = -0.0226 \]
\[ EF_{rdm} = \left[ 1 - \left( 1 + 0.32 \times 8.37 \times 70.1^{0.32} \times 2.4 \times \frac{1}{0.0120(1+0.0226) \times c_p)} \right)^{\frac{1}{0.32}} \right] = 0.5108 \]
\[ EF_{ac} = \left( \frac{89.8 - 54.0}{89.8 - 19.7} \right) = 0.5108 \]
Actual radiator heat output according to “NEHTMiR\(_{md}\)”:
\[ Q_{rac} = 1806 \, W \]
Heat output according to radiator effectiveness:
\[ Q_r = (89.8 - 19.7) \times 4186 \times 0.5108 = 1804 \, W, \, Q_{rac} = 1806 \, W, \, dQ_r = 0.0\% \]
Actual radiator return temperature: \( t_{rac} = 54.03 \, ^\circ C \)
The radiator return temperature according the “NEHTMiR\(_{md}\)” radiator effectiveness:
\[ t_{rdm} = 89.8 - 70.1 \times 0.5108 = 54.0 \, ^\circ C, \, dtr = 0.0\% \]

**Example 9.** \( q_{mx} = 0.0059 \, kg/s, \, t_s = 89.7 \, ^\circ C, \, t_i = 19.7 \, ^\circ C, \, \Delta t_1 = 89.7 - 19.7 = 70.0 \, K, \)
\[ D_1 = 0.0199, \, D_2 = -0.0721. \) \( (Q_{ac} = 1289 \, W, \, t_{rac} = 37.1 \, ^\circ C) \)

The radiator energy efficiency according “NEHTMiR\(_{md}\)”:
\[ d_m = 0.0199 \times \ln(0.0059) - 0.0721 = -0.0369 \]
\[ EF_{rdm} = \left[ 1 - \left( 1 + 0.32 \times 8.37 \times 70.0^{0.32} \times 2.4 \times \frac{1}{0.0059(1+0.0369) \times c_p)} \right)^{\frac{1}{0.32}} \right] = 0.7602 \]
\[ EF_{ac} = \left( \frac{89.7 - 37.1}{89.7 - 19.7} \right) = 0.7513 \]
Actual radiator heat output according to “NEHTMiR\(_{md}\)”:
\[ Q_{rac} = 1289 \, W \]
Heat output according to radiator effectiveness:
\[ Q_r = (89.7 - 19.7) \times 4186 \times 0.7513 = 1304 \, W, \, Q_{rac} = 1289 \, W, \, dQ_r = 1.2\% \]
Actual radiator return temperature: \( t_{rac} = 37.1 \, ^\circ C \)
The radiator return temperature according the “NEHTMiR\(_{md}\)” radiator effectiveness:
\[ t_{rdm} = 89.7 - 70.0 \times 0.7602 = 36.5 \, ^\circ C, \, dtr = 1.7\% \]

**The Discrepancy**

The discrepancy in the results of measurements and simulation calculations of the Radiator Delonghi-22 efficiency, radiator heat output and return temperature in terms of mass flow changes from 23% to 151% of the radiator nominal mass flow rate does not exceed 1.5%. 
6.3. Implementation of the “NEHTMiRmd” for High Ribbed Convective Radiator type-8RR

Data input:
\[ m = 0.30, \quad Ar = 3.99 \, \text{m}^2, \quad K_M = 1.912, \quad \phi = 8.20, \quad D_3 = 0.01124, \]
\[ D_4 = 0.3952. \]

The result of the measurement from 1 to 5 and simulation calculations of the High Ribbed Radiator-8RR effectiveness are presented on the Figure 33.

**Example 10.**
\[ q_{mx} = 0.0303 \, \text{kg/s}, \quad t_s = 51.2 \, ^\circ\text{C}, \quad t_i = 21.0 \, ^\circ\text{C}, \quad \Delta t_1 = 51.2 - 21.0 = 30.2 \, \text{K}, \]
\[ D_3 = 0.01124, \quad D_4 = -0.0721. \quad (Q_{ac} = 1289 \, \text{W}, \quad t_{rac} = 37.1 \, ^\circ\text{C}) \]

The radiator energy efficiency according “NEHTMiRmd”:
\[ d_m = 0.01124 \times 0.0303^{0.3952} = 0.00282 \]
\[ EF_{md} = \left[ 1 - (1 + 0.30 \times 1.912 \times 30.2^{0.30} \times 3.99 \times \frac{1}{0.003(1 - 0.0001 x c_{w})}) \right]^{1/3} = 0.149 \]

Actual radiator heat output according to “NEHTMiRmd”:
\[ Q_{rac} = 583 \, \text{W} \]

Heat output according to radiator effectiveness:
\[ Q_r = (51.2 - 21.0) \times 4186 \times 0.149 = 573 \, \text{W}, \quad Q_{rac} = 583 \, \text{W}, \quad dQ_r = 1.7\% \]

Actual radiator return temperature: \( t_{rac} = 46.6 \, ^\circ\text{C} \)

The radiator return temperature according the “NEHTMiRmd” radiator effectiveness:
\[ t_{rmd} = 51.2 - 30.2 \times 0.149 = 46.7 \, ^\circ\text{C}, \quad dtr = 0.2\% \]

**Example 11.**
\[ q_{mx} = 0.0047 \, \text{kg/s}, \quad t_s = 51.1 \, ^\circ\text{C}, \quad t_i = 21.0 \, ^\circ\text{C}, \quad \Delta t_1 = 51.1 - 21.0 = 30.1 \, \text{K}, \]
\[ D_3 = 0.01124, \quad D_4 = -0.0721, \quad (Q_{ac} = 352 \, \text{W}, \quad t_{rac} = 33.3 \, ^\circ\text{C}) \]

The radiator energy efficiency according “NEHTMiRmd”:
\[ d_m = 0.01124 \times 0.0047^{0.3952} = 0.0001355 \]
\[ EF_{md} = \left[ 1 - (1 + 0.30 \times 1.912 \times 30.1^{0.30} \times 3.99 \times \frac{1}{0.0047(1 - 0.0001 x c_{w})}) \right]^{1/3} = 0.602 \]

Actual radiator heat output according to “NEHTMiRmd”:
\[ Q_{rac} = 352 \, \text{W} \]

Heat output according to radiator effectiveness:
Example 12. The Discrepancy

The radiator return temperature according the “NEHTMiRmd” radiator effectiveness:
\[ t_{\text{rmd}} = 51.1 - 30.1 	imes 0.602 = 32.9 \, ^\circ\text{C}, \, d\tau r = -1.3\% \]

Example 13. \( q_{\text{m}} = 0.0226 \, \text{kg/s}, \, t_s = 59.0 \, ^\circ\text{C}, \, t_i = 22.0 \, ^\circ\text{C}, \, \Delta t_1 = 59.8 - 22.0 = 37.0 \, K, \)
\[ D_3 = 0.01124, \, D_4 = -0.0721, \, (Q_{\text{ac}} = 709 \, W, \, t_{\text{rac}} = 51.5 \, ^\circ\text{C}) \]

The radiator energy efficiency according “NEHTMiRmd”:
\[
\begin{align*}
\dot{m}_m &= 0.01124 - 0.0226^{0.3952} = 0.00251 \\
EF_{\text{rmd}} &= \left[ 1 - (1 + 0.30 \times 1.912 \times 37.0^{0.30} \times 3.99 \times \frac{1}{0.0226^{1-0.00251} \times c_p} \right]^{0.2058} = 0.720 \\
EF_{\text{ac}} &= \left( \frac{59.0 - 51.5}{59.0 - 22.0} \right) = 0.2024 \\
\end{align*}
\]

Actual radiator heat output according to “NEHTMiRmd”:
\[ Q_{\text{rac}} = 709 \, W \]

Heat output according to radiator effectiveness:
\[ Q_r = (59.0 - 22.0) \times 4186 \times 0.2058 = 721 \, W, \, Q_{\text{rac}} = 709 \, W, \, d\tau r = -1.7\% \]

Actual radiator return temperature: \( t_{\text{rac}} = 51.5 \, ^\circ\text{C} \)

The radiator return temperature according the “NEHTMiRmd” radiator effectiveness:
\[ t_{\text{rmd}} = 59.0 - 37.0 \times 0.2058 = 51.4 \, ^\circ\text{C}, \, d\tau r = 0.2\% \]

The Discrepancy

The discrepancy in the results of measurements and simulation calculations of the high ribbed convective \textit{Radiator-8RR} efficiency, radiator heat output and return temperature in terms of mass flow changes from 26% to 202% of the radiator nominal mass flow rate does not exceed 4.3%.

7. Conclusions

A revised \textit{New Extended Heat Transfer Model in Radiators NEHTMiRmd} is general and suitable for all types of radiators, both new radiators and existing radiators after a certain period of operation. It describes the heat transfer processes with very high accuracy in panel radiators (medium ribbed), iron elements radiators (not ribbed), convectors (high ribbed) not only in the nominal conditions - in which the radiators are designed, but what is particularly important also in the operating parameters when the radiators water mass flow rate changes from 10% to 200% of the nominal value and at the same time the supply temperature changes whole range of radiators operation during the heating season (in all tests range \textit{max} inaccuracies are below 4.3%).

In order to prove the general nature of the \textit{NEHTMiRmd} the comparison of the calculations and measurements results for older iron elements radiators previously commonly used in central heating installations, new plate radiators and convectors currently designed are presented.
Across a wide range of tests and measurements carried out for ribbed radiator Delonghi type 22, the discrepancy between the results obtained from simulation calculations based on the NEHTMiR_md and the actual values obtained from measurement’s in terms of mass flow changes from 23% to 151% of the nominal value—do not exceed 2.0%.

The discrepancy in the results of the measurements and based on the NEHTMiR_md simulation calculations for the Iron Elements Radiator T-1 in terms of mass flow changes from 39% to 179% of the radiator nominal mass flow rate—not exceed 2.5%.

In case of tests and measurements carried out for High Ribbed Convective Radiator type-8RRR across a very wide range of change: supply temperature from $t_s = 42.3$ °C to $t_s = 59.0$ °C and water mass flow from 29% to 258% of the nominal flow rate, maximum discrepancy between the measured and obtain from simulation calculations result according NEHTMiR_md—do not exceed 4.3%.

The additional thermography measurements of the temperature distribution on the radiators surface, in the entire range fully confirmed the results obtained from the simulation calculations based on the NEHTMiR_md.

This issue is particularly important in the case of the existing buildings after their refurbished, where central heating installations with substantial oversized radiators and with too high supply temperature operate during the heating season practically at a mass flow rate of 2-times to 4-times smaller than the nominal value [7,8,13].

Conducted analyses of the actual heat consumption in more than 600 refurbished buildings showed that the vast majority did not achieve the expected reduction in actual heat consumption (and in some cases actual consumption increased) [7] due to unproper operating conditions of radiators with to high supply temperature, low mass flow rate and the associated low energy efficiency of the heating systems. In such facilities there is an urgent need to develop “Individual projects” for the thermal and hydraulic adaptation of existing oversized central heating systems to new actual heat demand of the rooms, which is not possible without knowledge of the “good model” describing the heat transfer proces in radiators under these conditions.

In addition, in such building the individual heat cost allocators are commonly used and the current heat transfer model in radiators according to EN 442 is used for their software. As the measurements and analyses carried out have shown, errors due to differing significantly from the nominal radiators operating conditions and the incorrect installation point of the heat cost allocators reach up to 40%, [13].

Achieved the high compatibility of the results of the simulation calculations with the measurement results for different types of radiators: Iron Elements, Plate Radiators, Convectors in a very wide range of changes in the water mass flow rates and the supply temperature indicates that the developed NEHTMiR_md model is also essential for:

- directly assessing the actual energy efficiency of the heating system in the heating season.
- improve the indications of the heat allocator due their proper programming in the Individual Heating Costs Allocation Systems [14].
- to establish the suitable conditions for operational regulation of the Central Heating Installations especially in existing buildings after their refurbishment as well as for the District Heating Systems with substantial oversized heat exchangers.

Verified NEHTMiR_md can also be used in: designing and simulating calculations of the central heating installations, for the rational conversion of the existing installations and district heating systems into low temperature energy efficient systems.

In addition, it may form the basis for an appropriate modification of the EU Standards regarding the scope and test conditions of the radiators.

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Abbreviations
The following abbreviations are used in this manuscript:

DOAJ Directory of open access journals
TLA Three letter acronym
LD Linear dichroism

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