# Dynamic behaviour of the panel radiator

Ing. Jindřich Boháč

Vedoucí práce: Prof. Ing. Jiří Bašta, Ph.D.

***Abstrakt***

*Článek je zaměřen na sledování, rozbor a popis tepelné dynamiky deskového otopného tělesa mimo tepelně ustálený stav. Základem je rozložení teplotního pole na čelní straně teplosměnné plochy sledované termovizní kamerou. Sledováno bylo těleso Korado Radik klasik typu 10 v modulovém rozměru 500 x 1000 mm s jednostranným napojení shora dolů ve fázi náběhu. Termogram čelní desky byl rozdělen na 9 plošně shodných částí a v každé této části pak byly graficky nalezeny hodnoty doby dopravního zpoždění ($T_d$), doby průtahu ($T_u$), doby náběhu ($T_n$), časové konstanty ($\tau$) a setrvačností náběhu $T_{n63}$ a $T_{n90}$, coby dynamické veličiny popisující rychlost změny tepelného stavu. Je zde popsán vztah těchto hodnot vzhledem ke geometrii konkrétního tělesa a závislost jejich změny na čase. Práce tak čerpá z poznatků vzešlých z prací řešených na Ústavu techniky prostředí a dále je prohlubuje.*

***Klíčová slova***

*Deskové otopné těleso, dynamický děj, náběh, termovize, experiment, model.*

***Abstract***

*This article deals with the monitoring, analysis and description of the thermal dynamic processes of a panel radiator outside the thermally steady state. Analysis is based on the layout of the temperature fields on the frontal heat transfer surface of radiator. Surface was monitored by thermal camera. It is focused on the specific panel radiator - Korado Radik Classic type 10 with dimensions 500 x 1000 mm with a single side connection to a heating system from the top to the bottom. Heating appliance was observed only in phase of heat-up, i.e. stage of increasing of heat output. The thermography image of the whole front panel of the radiator was divided into 9 equal areas. In each of those sectors were graphically found dynamic variables describing rate of change of thermal state: dead time (or transport delay) ($T_d$), process delay ($T_u$), process reaction rate ($T_n$), time constant ($\tau$) and speed of response $T_{n63}$ and $T_{n90}$. The relationship of these values relative to the geometry of a radiator body and the dependence of their changes in time are also described in this paper. Article draws and further deepens knowledge arising from experiments performed at the Department of environmental engineering.*

***Keywords***

*Panel radiator, dynamic behavior, heat-up, thermography, experiment, model.*

## 1. Introduction

Covering of the heat losses and the creation of thermal comfort using panel radiators is the most represented way of heating in residential buildings today. This is primarily due to their acquisition price, easy to install and last but not least today conventional design modifications according to customer requirements. With such a number of applications grow up importance of efficiency and optimization of their operation. The aim of findings described in this article, with regard to the physical possibilities, is to contribute to such optimization. Therefore requirements applicable to control, accuracy and reliability are also grown. These are all of unambiguous reasons why examine the dynamic behaviour of the radiators.

It is necessary to generally distinguish two dynamic processes during the operation of each radiator – increasing and decreasing of heat output (i.e. heat-up and cool-down of a radiator). The operation of a radiator is more often in the phase of heat-up and cool-down than in a nominal steady state during the heating season. It is due to constantly changing temperature conditions or users requirements. For detailed analysis see [1] or [2]. Both these processes are characterized by, among others, its step response and response curve. It is dependence of changes of heat output (in case of using thermal camera it is change of surface temperature) on time. Typical curve shape for cool-down of radiators is according to first-order system. So it could be relatively easy mathematically described as in [3]. In contrast, for heat-up, the situation is much more complex and therefore this article is dedicated only to heat-up process.

We don't know what will be order of response curve for a specific radiator, at the beginning of the heat-up process. But it has at least the second or higher order. This is due to the heat-up principle, when many constant parameters during cooling becomes variable. The unknown, among other, becomes the area of heat transfer surface, by which currently radiator emits heat output to its surrounding. There is gradual extrusion of the existing water content about temperature balanced with the surrounding with supply water at a higher temperature.

The problem is that there is currently no single reliable methodology for the determination of dynamic parameters which taking place in the radiators. Dynamics can be quite accurately determined by measuring and expressed by dependence of the surface temperature on time, but only for certain types of radiators. Speed of response, time constant, dead time and process reaction rate are all very important quantities for design and ensure of optimum control of the heat output of radiator. They are the basis for design and selection of suitable controllers, because their controlling behaviour, as it is proved in [2], is completely different for different phases of the heat output spectrum of a radiator. The controller must response dynamically to disturbances, therefore it must "know" the dynamic behaviour of a radiator, which could be expressed, among others, by parameters mentioned above.

The importance of basic dynamic parameters and their knowledge is evident. To simplify the process of finding necessary data, i.e. eliminating the need of experiment, we aim at create a model of the dynamic behaviour of radiators in MATLAB Simulink software. This model expresses heat transfer from fluid through the heat transfer surface to the air flowing around radiator. So it is necessary to study the dynamic variables of specific radiators in details and then generalize these findings.

## 2. Experiment

It was selected basic type of a radiator 10 with dimensions of 500 x 1000 mm. It was subjected to measuring for understanding how the so-called active heat transfer surface progress. It was connected in nominal manner – single side from the top to the bottom. At first we had to determine and set nominal parameters of temperature and mass flow rate of the water through the radiator. Then was used thermal camera for taking (each 5 seconds) a series of thermography images during a heat-up phase. Thus we obtain dependence of the radiator surface temperature on time in each individual point (pixel), which the camera sensor is able to distinguish. Within the area of one thermography image, which is usually equal to entire frontal projection surface of a radiator, may be evaluated mean surface temperature of the radiator $t_p$ [4]. This allows a fact based on the principle that the heat transfer on the side of the water is far more intense than the heat transfer on the side of the air. The thermal conductivity coefficient of a material of radiator is high and the thickness of the wall of radiator is relatively small, at the same time. In such an arrangement it is possible to neglect water temperature drop during heat transfer on the water side and the heat conduction in material of the radiator. It will not allow error greater than 5% and therefore the mean temperature of the water $t_{wm}$ is approximately equal to the mean surface temperature of the radiator $t_p$. The process is tracked from initial changes of mean surface temperature (i.e. without dead time) until steady state of equilibrium. Then, using the procedure described in [2], the heat-up characteristic curve can be converted from dependence of mean surface temperature on time to dependence of relative heat output on the time.

## 3. Evaluation procedure

All dynamic variables described above have been determined according to procedure based on the method of the tangent at the inflection point. This means replacing response (characteristic curve) of high-order system by first-order curve with dead time [5]. The result is shown in Figure 1, where obtained step response is expressed as a dimensionless rise of the heat output (relative heat output) of the specific radiator. Resulting evaluated dynamic variables are of course strongly dependent on type of examined radiator. Values of speed of response $T_{n63}$ a $T_{n90}$ are fully in conformity with previously obtained data, which was presented, among others, at conference Heating in Třeboň 2013 [1].

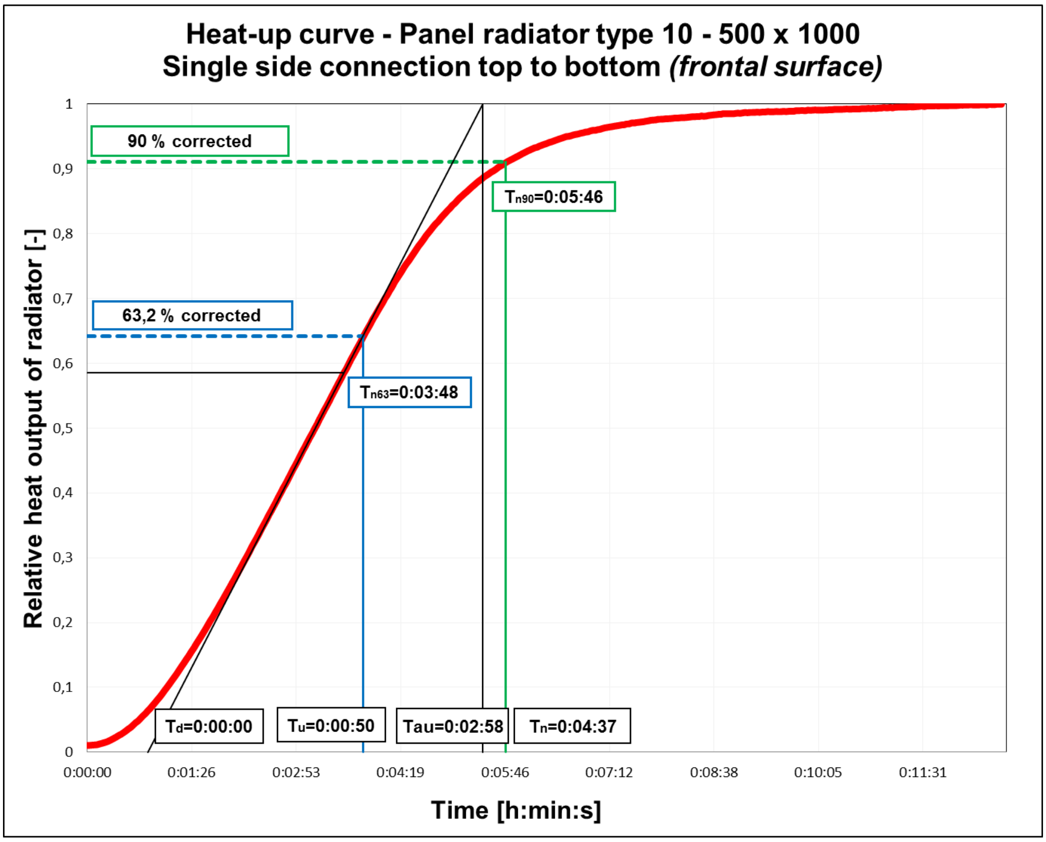


***Fig. 1.*** *Heat-up curve of relative heat output of a panel radiator Korado Radik classic type 10 with dimensions 500 x 1000 mm for entire frontal projection surface.*

Originally entire frontal heat surface was symmetrically divided into 9 areas according to a simple diagram in Figure 2. It was done in order to get an overview of the dynamics in different parts of the radiator and to determine progress of active heat transfer surface. Individual sectors during the heat-up phase, of course, influence themselves and purpose of distributing of frontal surface is to describe how much. We also need assess importance of individual dynamic variables in order to predict the progress of active heat transfer surfaces without experiments.

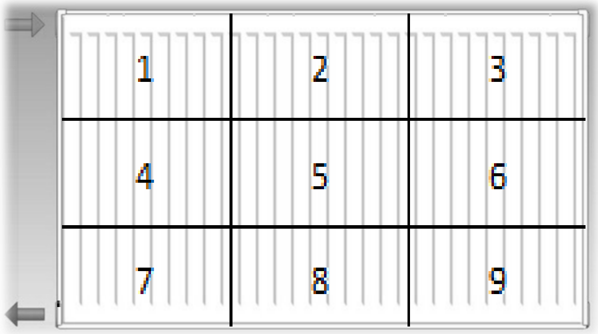


***Fig. 2.*** *Diagram of fragmentation entire frontal projection heat transfer surface of panel radiator into 9 symmetrical areas.*

The distribution of frontal surface into a certain number of smaller areas in the direction of the length of the radiator or its height also give us a clearer picture how the dimensions of a radiator influence thermal dynamics. Generally, there is observed dependence of dynamic parameters on static parameters. Resulting values of these parameters are, of course, strongly depending on the connection of a radiator to the heating system. In each sector were, in the same manner as for the entire frontal surface, evaluated heat-up curves and variables arising from them. The timeline is in all the figures maintained in the same range for the purpose of easy comparison of the individual response curves.

## 4. Evaluated results

Due to limitation of length of this text it is not possible to present a response curves of all sectors, therefore only three are selected. They clearly show differences during heat-up phases of sectors 2, 6 and 9 (Figures 3 – 5). For example in sector 9 is in time of 2 minutes and 53 second heat output of this part only about 6%, while heat output of the sector 2 is more than 90%. This is crucial difference in point of view of description of an active heat transfer surface. Most of all it is dependent on the connection type, in this case.

This difference in values of heat output between individual sectors can be described using the analysis of individual dynamic variables and we have to evaluate factors that influence them. Table 1 summarizes these variables for individual sectors and also for comparison for the entire frontal surface too. Evaluated were dead time ($T_d$), process delay ($T_u$), process reaction rate ($T_n$), speed of response $T_{n63}$ and $T_{n90}$ and time constant ($\tau$).

***Table 1.*** *– Dynamic variables evaluated from response curves.*

| Dynamic variables [h:min:s] | Entire frontal surface | Sector No. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| $T_d$ | 0:00:00 | 0:00:00 | 0:00:12 | 0:00:18 | 0:00:08 | 0:00:30 | 0:00:36 | 0:00:36 | 0:00:42 | 0:00:42 |
| $T_u$ | 0:00:50 | 0:00:19 | 0:00:20 | 0:00:19 | 0:01:45 | 0:01:22 | 0:01:05 | 0:02:37 | 0:02:29 | 0:02:15 |
| $T_n$ | 0:04:37 | 0:02:03 | 0:01:52 | 0:01:55 | 0:02:13 | 0:02:20 | 0:02:39 | 0:02:54 | 0:02:57 | 0:03:10 |
| $T_{n63}$ | 0:03:48 | 0:01:38 | 0:01:32 | 0:01:36 | 0:03:12 | 0:02:52 | 0:02:50 | 0:04:32 | 0:04:24 | 0:04:20 |
| $T_{n90}$ | 0:05:46 | 0:02:44 | 0:02:42 | 0:03:10 | 0:04:30 | 0:04:10 | 0:04:22 | 0:06:18 | 0:06:08 | 0:06:12 |
| $\tau$ | 0:02:58 | 0:01:19 | 0:01:12 | 0:01:17 | 0:01:27 | 0:01:30 | 0:01:45 | 0:01:55 | 0:01:55 | 0:02:05 |

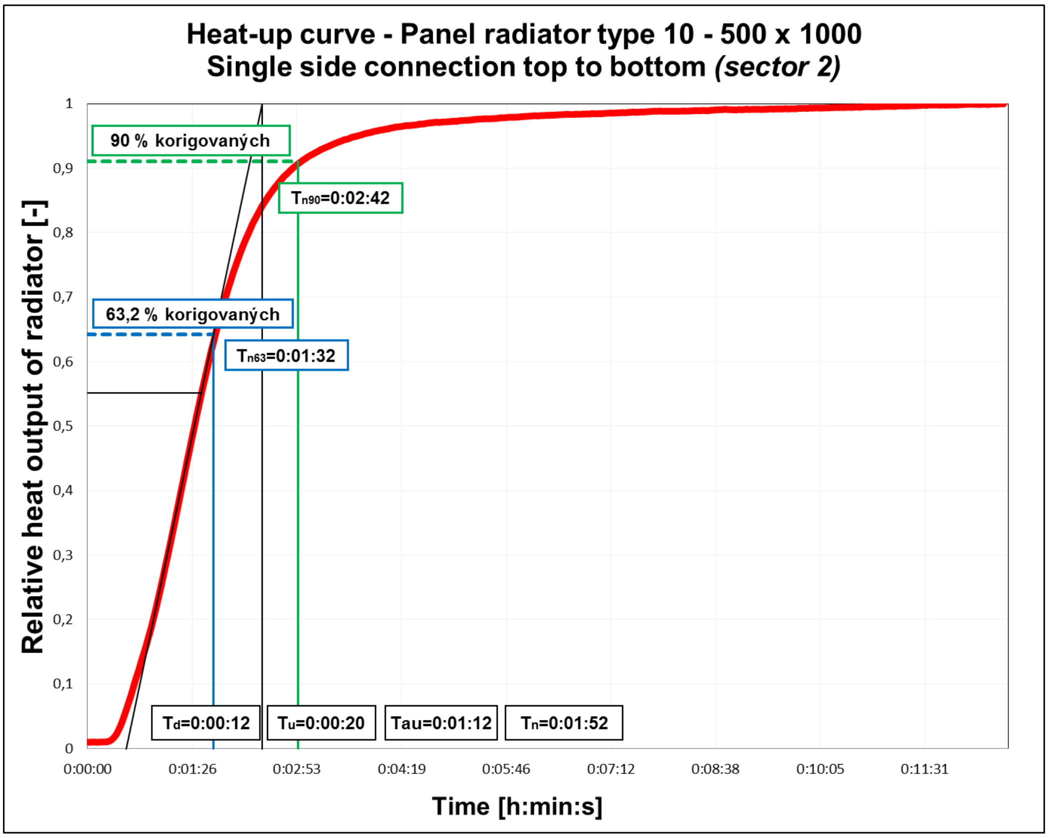


***Fig. 3.*** *Heat-up curve of relative heat output of a panel radiator Korado Radik classic type 10 with dimensions 500 x 1000 mm for sector 2.*

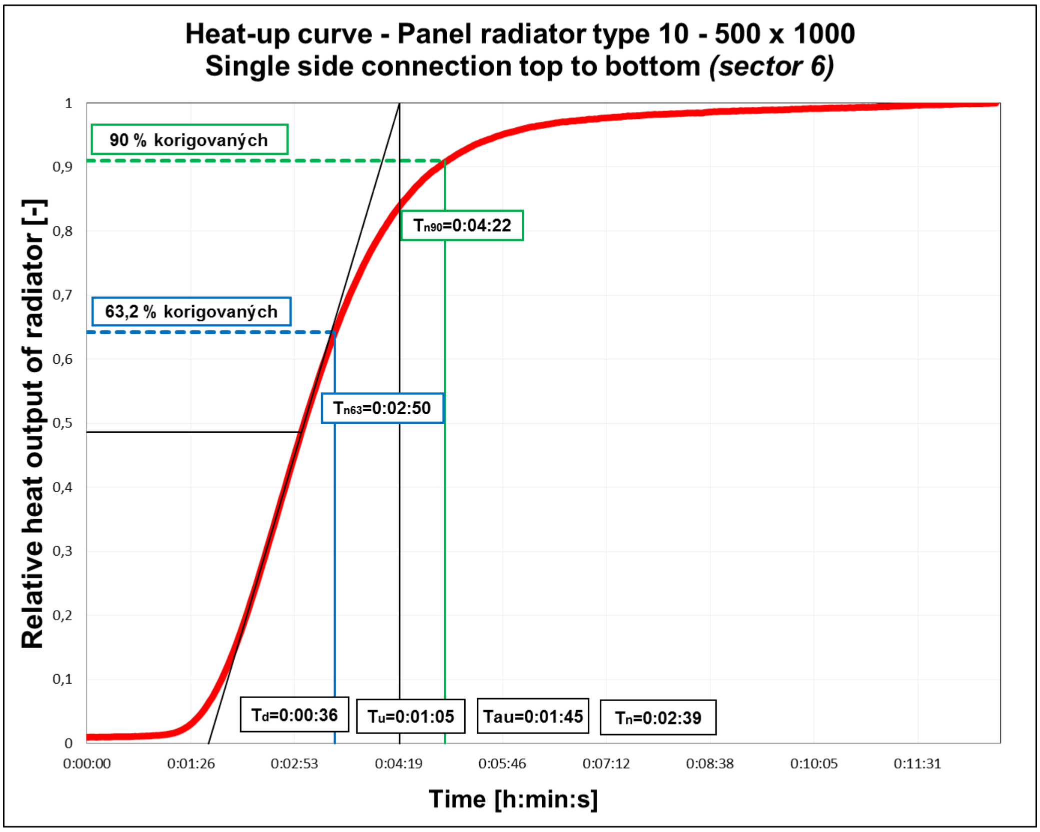


***Fig. 4.*** *Heat-up curve of relative heat output of a panel radiator Korado Radik classic type 10 with dimensions 500 x 1000 mm for sector 6.*

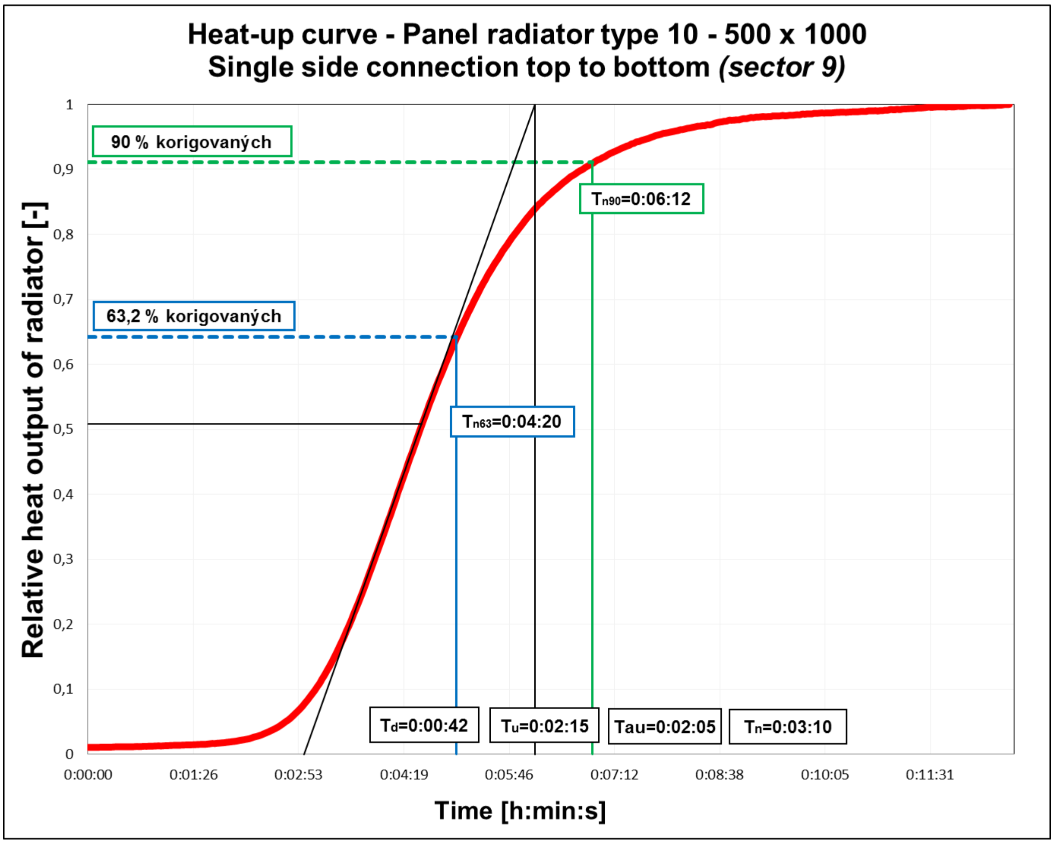


***Fig. 5.*** *Heat-up curve of relative heat output of a panel radiator Korado Radik classic type 10 with dimensions 500 x 1000 mm for sector 9.*

## 5. Data interpretation

It is necessary to assess trend of progress of individual parameters in relation to the height and length of the radiator, i.e. the dependence on the geometry of the radiator. There is detailed verbal assessment also expressed very clearly graphically too in [6]. Knowledge of the dynamic parameters referred in table 1 helps us better grasp issue of regulation of heat output in order to optimization of operation of regulators and, of course, radiators. In terms of evaluation method for dynamic behaviour and further use are the most important parameters dead time ($T_d$), process delay ($T_u$) and process reaction rate ($T_n$).

For all observed parameters is quite clear, that they depend primarily on the height of the radiator and in the direction of its length does not change with such intensity or they are almost constant. Except sectors comprising distribution chamber (in this case sectors 1 to 3).

Progression of active heat transfer surface is determined according to dead time in dependence on fragmentation of frontal surface. Let assume that once initial increase of mean surface temperature of sector reaches at least 0.1 K, then this sector is identified as a heat sharing active surface. A more accurate prediction of progression active heat transfer surface is obtained by dividing the entire front surface to more parts. But the division to only twice number of sectors represents much more difficult process of evaluation and results will not differ in fundamental parameters.

Progression of the active heat transfer surface in time for 9 evaluated sectors is shown in Figure 6. We can find (by interleave points with corresponding curve and under the above mentioned assumption) that radiator emits heat with its entire frontal heat transfer surface after approximately 40 seconds from the initial entry of the supply hot water.

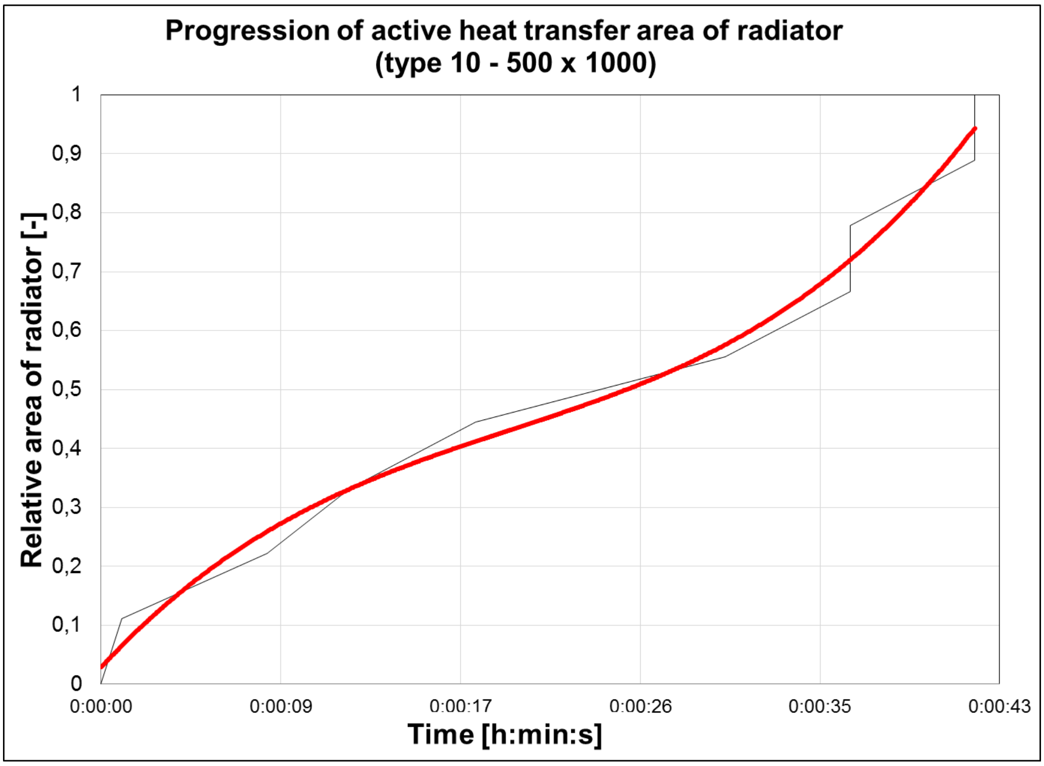


***Fig. 6.*** *Progression of active heat transfer surface of panel radiator type 10 with dimensions 500 x 1000 mm.*

It was also examined [6] a double length radiator. It was confirmed a strong dependence of dynamic parameters on the geometry of the radiator, i.e. on its type, height and length. Thus we can assume that for the so-called "long" radiators (i.e. with ratio of length to height greater than 3) will not be valid almost exclusive dependence of dynamic parameters on height of the radiator. For individual, at least different types of radiators, it is therefore necessary to evaluate, establish and generalize specific geometrical parameters according to which it will be possible to predict the progression of active heat transfer area or surface.

## 6. Use of results

The dynamics of the temperature field of radiator can be observed and evaluated relatively accurately using thermal imaging technology. However it is a lengthy and financial demanding process. This analysis is therefore trying to describe this process mathematically. With regard to the phenomenon under consideration, i.e. the progress of relative heat output, it is possible to advantageously introduce dimensionless parameter $\varepsilon$. I is based on fundamental principles that describe the transmission of heat through the heat emitting surface. It can be called change of transmitted heat coefficient and takes the form:

$$\varepsilon = \frac{Q_{actual}}{Q_N} = \left(\frac{\Delta t_{actual}}{\Delta t_N}\right)^n \cdot \frac{S_{actual}}{S_N} \cdot \frac{T_d + T_u}{T_n} \tag{1}$$

There are used values obtained from analysis of dynamic behaviour. There are not just individual times, but mainly relative surface (i.e. ratio of active and nominal surface) of the radiator during heat-up phase (see Figure 6), although currently only for a given type. Next stage is to carry out their generalization, so that coefficient could be practically. There is used temperature exponent of the radiator *n* in formula (1). Exponent may essentially individualize formula (1) for the specific radiators, because it is always given by the manufacturer of the radiator. In conformity with findings of this article the temperature exponent also depends mainly on the height of the radiator and only minimally on its length (if we are not talking about convectors). Temperature differences are determined arithmetically or logarithmically (depending on the temperature ratio factor *c*) in the same manner as in recalculation of heat output of radiators.

## 6. Software model

It is possible to evaluate heat-up process without the experiment in another way. On the basis of analysed values, especially progression of active heat transfer surface, is currently being developed dynamic model in MATLAB Simulink [5]. It is based on the principle of the basic calorimetric equation. There is also solved the heat transfer to the surroundings separately in different parts of the radiator. However at present it is not known such a functional model that would provide reliable and applicable results for the control and regulation of heat output of various kinds or types of radiators.

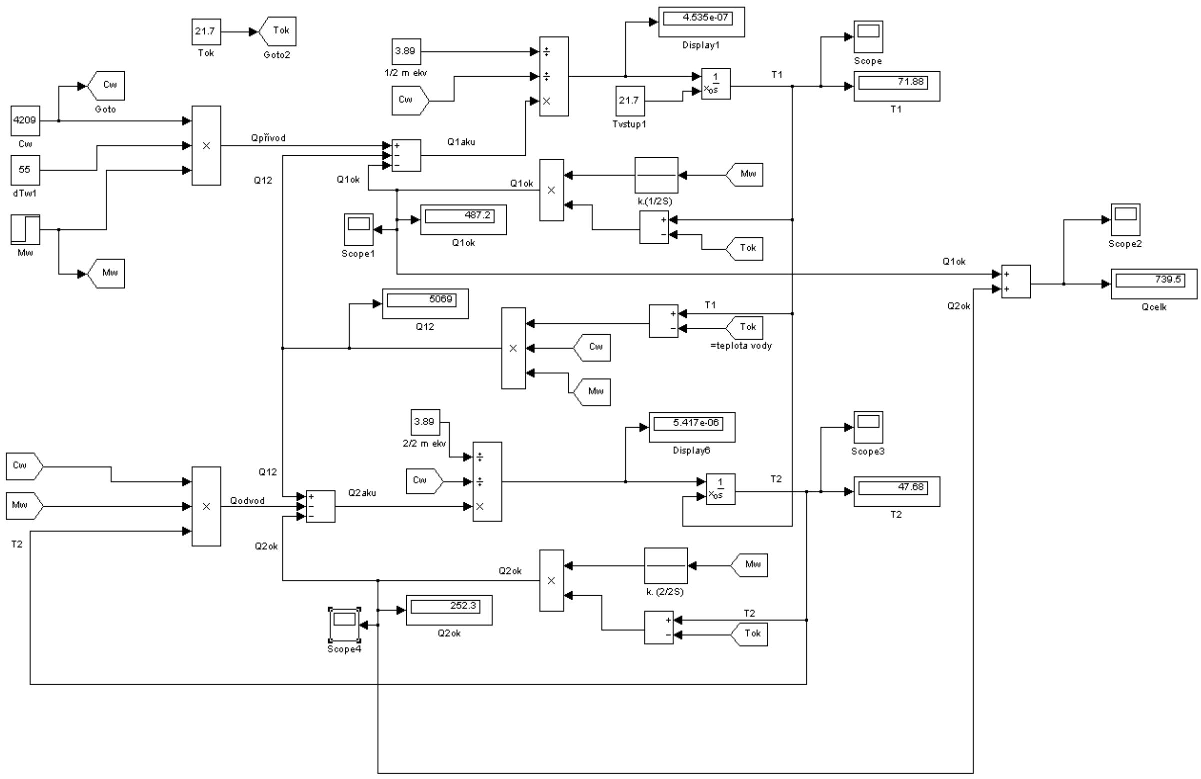


***Fig. 7.*** *Dynamic model in MATLAB Simulink software for heat-up phase of panel radiator type 10 with dimensions 500 x 1000 mm connected from the top to the bottom.*

## 7. Conclusion

Currently there is no single reliable methodology for evaluating of dynamic behaviour of different types of radiators. The aim of my thesis is to describe this methodology and to find such determination method for dynamic variables which would be applicable to more than one type of radiator. It will help to improve controllability and increase the efficiency of operation of radiators. It is naturally possible measure necessary values but in many cases it is very time consuming. Mainly in case of measurement using thermography, it is also very demanding on technical equipment. Above all, only measuring can help us to find those inputs that would enable mathematical description and simulation.

Dynamics processes express heat output of radiators is a very complex matter due to diversity of radiators. There are endless ways of designs, kinds and types of radiators. Probably it will not be possible include all designs of radiators into one software model. However if we will be able to identify behaviour of the most used panel radiators, it will be a success. Individual software models of behaviour or models with different specified inputs must always be confronted with measurement results.

It was described in this paper one of the procedure of analysis of dynamic parameters. It is based on the observed temperature profile of frontal surface of radiator in relation to geometry of the radiator. This is an approach that could help to establish some general values and assumptions, at least for "short" and "medium-long" panel radiators.

***Acknowledgement***

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS13/182/OHK2/3T/12.

***Symbols***

| | | |
|---|---|---|
| $c$ | temperature ratio factor | [-] |
| $\Delta t_{actual}$ | actual temperature difference | [K] |
| $\Delta t_N$ | nominal temperature difference | [K] |
| $\varepsilon$ | change of transmitted heat coefficient | [-] |
| $n$ | temperature exponent of the radiator | [-] |
| $Q_{actual}$ | actual heat output of the radiator | [W] |
| $Q_N$ | nominal heat output of the radiator | [W] |
| $S_{actual}$ | actual (active) heat transfer surface of the radiator | [m$^2$] |
| $S_N$ | nominal heat transfer surface of the radiator | [m$^2$] |
| $T_d$ | dead time | [s] |
| $T_u$ | process delay | [s] |
| $T_n$ | process reaction rate | [s] |
| $T_{n63}$ | speed of response for 63 % of final value of heat output | [s] |
| $T_{n90}$ | speed of response for 90 % of final value of heat output | [s] |
| $\tau$ | time constant | [s] |

***References***

[1] Boháč, J., Bašta, J.: Dynamické chování otopných těles s ohledem na regulační zásah. *Konference vytápění Třeboň 2013.* Praha: Společnost pro techniku prostředí, 2013, s. 120 – 124. ISBN 978-80-02-02431-6.

[2] Boháč, J.: Dynamické chování otopných těles. *Diplomová práce.* Praha: ČVUT, 2012, 136 s.

[3] Jančík, L., Bašta, J.: Posouzení dynamického chování otopných těles termografickou metodou. *5. Konference simulace budov a techniky prostředí SBTP´08*. Brno: IBPSA-CZ, 2008, s. 45 – 49. ISBN 978-80-254-3373-7.

[4] FLIR Systems. *ThermaCam Researcher: User´s manual.* Rev. a74, 2004. 146 s.

[5] Boháč, J., Bašta, J.: Experimentální podklady pro dynamický model chování deskového otopného tělesa. *8. Konference simulace budov a techniky prostředí IBPSA-CZ.* Praha: IBPSA-CZ, 2014, s. 101 – 106. ISBN 978-80-260-7209-6.

[6] Boháč, J.: Dynamické chování otopných ploch ve vazbě k řízení jejich tepelného výkonu. *Studie disertační práce*. Praha: ČVUT, 2014. 56 s.