CHEMICAL ENGINEERING TRANSACTIONS

VOL. 52, 2016

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Peng-Yen Liew, Jun-Yow Yong, Jiří Jaromír Klemeš, Hon Loong Lam

ISBN 978-88-95608-42-6; **ISSN** 2283-9216

DOI: 10.3303/CET1652083

Numerical Simulation and Thermographic Examination of the Heat Transfer in a Radiator

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Investigations of the heat transfer by conduction and natural convection in a radiator used in electronic equipment were carried out. On the basis of a physical model, 3-D geometrical model of the radiator was developed in COMSOL Multiphysics software. Using the finite-element method, numerical simulations were performed to determine temperature distribution at the radiator surface.
In order to validate the numerical model of the heat transfer, an experimental setup comprising an electric heating coil, radiator and thermovision camera FLIR SC7600 was assembled. By varying the voltage, the heat flow supplied by the heating coil was varied. The steady-state temperature distributions at the radiator surface were recorded using the thermovision camera, and parameters of the convective flow field in the surrounding air were measured by anemometry.
Positive results of the validation of the numerical model indicate that thermovision is a suitable experimental tool for this kind of application. Numerical simulation combined with thermographic techniques can be conveniently used in developing new radiator designs.

1. Introduction

Numerical simulations are an essential tool of modern engineering. Using simulation models based on approximate description of physical phenomena and processes, it is possible to pre-test objects under design so that their essential features can be defined, as well as optimized. The essential problem is to describe the analysed object in a consistent manner taking all its features into account. Other problems are the quality, reliability and accuracy of the numerical calculations performed to describe the physical phenomena and processes.
When numerical methods to solve partial differential equations are used, a set of possible solutions is determined first, and then – on the basis of initial conditions –the final solution is identified. The difficulty, however, is in the correct definition of boundary conditions. According to Roache (1998) in order to assess the level of accuracy and reliability of numerical simulations their verification and validation must be carried out. Verification is a phase aimed at answering the question if the equations describing the tested model have been properly solved, whereas the aim of validation is to answer the question whether or not relevant equations have been chosen to model the physical phenomena and processes. It is assumed here that in the validation study, the correctness of the model is evaluated on the basis of experimental measurements.
This article is concerned with numerical simulations of the heat transfer through a radiator using COMSOL Multiphysics software. Although its capabilities are considerable and confirmed by a wide range of practical applications, a critical evaluation of the simulation results is essential. A description of COMSOL modelling principles can be found in (Pryor, 2012). In order to validate the numerical model a test stand was built on which the experiments were performed with the use of thermovision. It is a continuation of the research on the use of thermovision as a validation tool for numerical models, conducted by Wernik and Wołosz (2015) and discussed also by Urbaniec et al. (2015).

Please cite this article as: Grabowski M., Urbaniec K., Wernik J., Wołosz K. J., 2016, Numerical simulation and thermographic examination of the heat transfer in a radiator, Chemical Engineering Transactions, 52, 493-498 DOI:10.3303/CET1652083

2. Numerical model of the radiator

2.1 Basic assumptions

In order to work out an adequate numerical model, the approach based on comparing computer simulations carried out using COMSOL Multiphysics suite with the measurements performed on a real device was developed. One of the most commonly used methods to build approximate numerical models is the finite element method (FEM). It allows to search for solutions of partial differential equations after the discretization of these equations using grid elements. The grid elements are considered as fragments of discretized area having uniform properties. Examples of FEM application were presented by Baskharone (2014). Figure 1 illustrates the development of the numerical model of the radiator. The geometrical model was built using CAD tools of COMSOL Multiphysics suite.

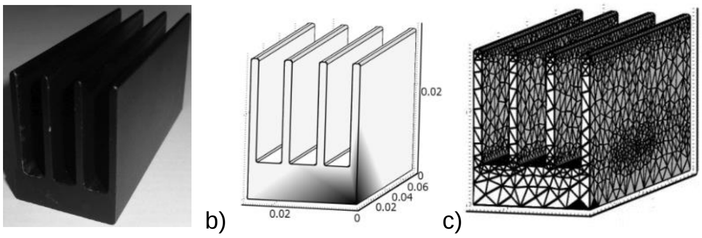


Figure 1: Geometry of the modelled device: a) view of the real object b) 3-D model c) FEM mesh

The geometrical model consisted of 15,957 tetrahedral elements. It was assumed that the heat is transferred by conduction from the base through the radiator and subsequently dissipated by natural convection from the surface of radiator fins to the ambient air. Three values of the thermal power were selected for the simulation and experimental studies, namely 0.78 W, 1.87 W and 17.74 W.

2.2 Conditions of heat transfer

Experimental determination of the heat transfer coefficients in convection conditions is a complex issue (Chow et al., 2015). In the literature, many empirical correlations determining the conditions of the convective heat transfer can be found. In general, the intensity of the convective heat transfer can be expressed by the following equation:

$$q=h(T_{ext} - T_{amb}) \tag{1}$$

where q is the average heat flux lost from the radiator surface, h is the average convective heat transfer coefficient, T_{ext} and T_{amb} denote temperatures of radiator surface and ambient, respectively.

A dimensionless representation of coefficient h is the Nusselt number:

$$Nu=(h \cdot l)/k_a \tag{2}$$

where l is characteristic length of the radiator surface, k_a is thermal conductivity of air.

Regarding the heat transfer by natural convection, most commonly used are the correlations based on the dimensionless numbers of Grashof (Gr), Prandtl (Pr) and Nusselt (Nu):

$$Nu=C(Gr \cdot Pr)^c \tag{3}$$

where coefficients C and c depend on the value of product $Gr \cdot Pr$.

For the purpose of this research the correlation proposed by Churchill and Chu (1975), valid at Gr*Pr* ≤ 10^9, was applied:

$$Nu = 0.68 + \frac{0.67(Gr \cdot \mathrm{Pr})^{1/4}}{\left[1+\left(\frac{0.492}{\mathrm{Pr}}\right)^{9/16}\right]^{4/9}} \quad \text{if } \mathrm{Gr}Pr \leq 10^9 \tag{4}$$

The values of the convective heat transfer coefficient determined from Eq(2) and dimensionless numbers that can be used in Eq(4), determined for the three values of the thermal power are shown in Table 1.

Table 1: Experimentally determined values of the dimensionless numbers and heat-transfer coefficient

Case	1	2	3
Heat flux at radiator base, *q* [W/m^2]	412.7	989.4	9,386
Grashof number, *Gr*	27,625	49,619	258,195
Nusselt number, *Nu*	6.06	7.69	11.27
Heat transfer coefficient, *h* [W/(m^{2}K)]	4.76	6.04	8.85

2.3 Boundary conditions

For the purpose of numerical simulation the following data were used:

- Thermal conductivity of aluminium k_{Al} =180 W/(mK),
- Ambient temperature 295 K,
- Thermal conductivity of air k_a=0.0256 W/(mK),
- Heat flux transferred from the base of the radiator for three cases in accordance with Table 1,
- Convective heat transfer coefficients for three cases in accordance with Table 1.

3. Thermographic investigation

Figure 2 illustrates the experimental procedure based on the use of the thermovision camera. The heating resistor was responsible for providing the thermal input and the power level was adjusted by the high current amplifier. The amplifier was controlled from the PC via a control program written in LabView environment. Convective air flow over the radiator was monitored and the flow velocity was measured using VelociCheck 8330 Air Velocity Meters placed 20 mm above the radiator. Temperature changes were recorded by FLIR SC7600 camera for which the NETD (Noise Equivalent Temperature Difference) parameter is 20 mK. By comparison with a reference surface (Scotch Super 33+ 3M duct tape) of constant known emissivity, the emissivity of the painted radiator surface was experimentally determined to be 0.96. The signal from the camera was transmitted to the PC in which thermal images of the tested radiator were computed.

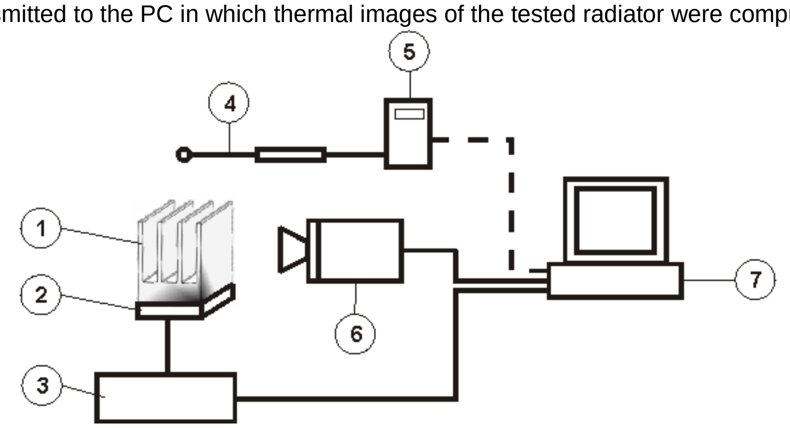


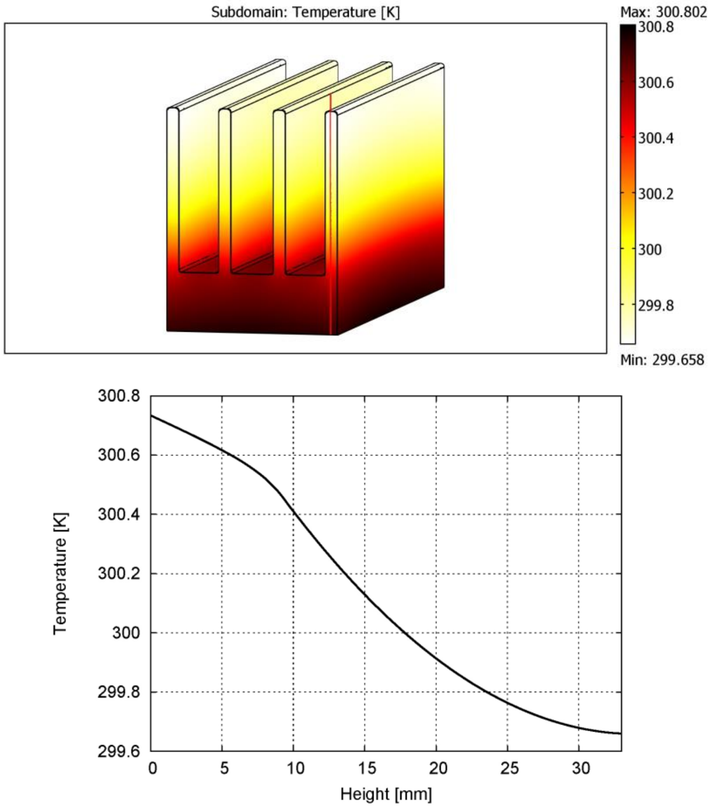
Figure 2: Scheme of the measurement stand. Markings: 1 Radiator, 2 Heater, 3 High current amplifier, 4 Probe, 5 Anemometer, 6 Thermovision camera, 7 PC. The dashed line - manual transfer of information

As an area that meets the above criteria a surface of Scotch Super 33+ 3M duct tape was adopted. Comparative measurement for the surface of the radiator covered with paint allowed to estimate the emission value for 0.96.

4. Results and discussion

4.1 Numerical simulations

As a result of numerical simulation, spatial distribution of the field of physical parameters of the tested radiator model is obtained in the form of vectors that can be used to generate two-dimensional images. Figure 3 shows the temperature distribution at the radiator surface at thermal power of 0.78 W as well as a graph showing the temperature along the height of the radiator.



a) b)

Figure 3: Temperature distribution: a) at the radiator surface, b) along the radiator height

4.2 Thermovision measurements

Experimental measurements employing the thermovision camera were performed at the ambient temperature of 295 K. From the obtained thermal images, distributions of the actual temperature values on the surface of the radiator were determined and average values of the surface temperature were calculated for each of the three values of the thermal power as shown in Table 2. On the basis of Eqs.(4) and (2), the average values of temperature and temperature differences were subsequently used to determine the values of the convective heat transfer coefficient.

Table 2: Temperature values [K] calculated from the thermographic measurements

Case	1	2	3
Average temperature of the radiator surface	300.3	304.6	348.4
Temperature difference between the radiator and the environment	5.3	9.6	53.4
Temperature difference between the base and top of the radiator	1.04	1.52	3.23

Figure 4 shows a thermogram obtained for thermal power of 0.78 W. The data recorded during thermographic measurements make it possible to investigate details of the spatial temperature distribution as for each point at the radiator surface, the values of height (originally expressed in pixels) and temperature (expressed in K) are available. Line 1 in Figure 4 indicates the points from which sample values of the temperature were taken, and Figure 5 presents the resulting diagram of temperature distribution along the height of the radiator, i.e. from the base to the top of the radiator fin.

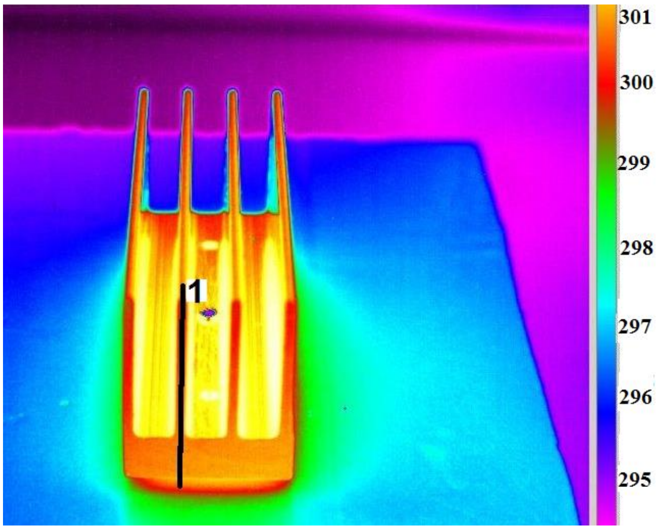


Figure 4: Thermogram of the radiator

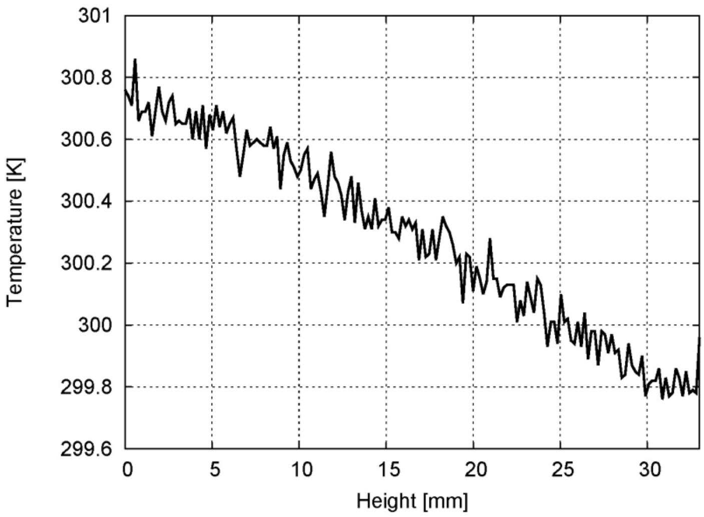


Figure 5: Temperature distribution along the selected line

Table 3 shows the values of air flow velocity above the radiator measured using VelociCheck 8330.

Table 3: Measurements of the flow velocity of air

Case	1	2	3
Flow velocity [m/s]	0.01	0.03	0.17

4.3 Discussion and outlook

A comparison between the simulated temperature distribution shown in Figure 3 and the experimentally determined one shown in Figure 5 indicates that the simulation model of the heat transfer has been successfully validated.

After necessary modifications and extension of the numerical model, the presented approach to heat dissipation from radiator surface will be used in further research on the heat transfer by forced convection when the air flow along the radiator is induced by a fan. The measurement stand will also be modified by adding the fan of the type used in the cooling systems of electronic devices.

5. Conclusions

Simulations performed by numerical methods, like FEM that has been widely used for decades, always yield approximate results. In this study, the results of numerical simulation of temperature distribution were experimentally validated by thermographic measurements. The operation of a conventional radiator with the height of 33 mm was studied under natural convection conditions. The numerical simulations and experimental measurements were performed for three values of the thermal power. The data recorded by a thermovision camera made it possible to determine the distributions of local temperature of the radiator surface and to calculate temperature values averaged over the radiator surface. The average values of the temperature were used to determine convective heat transfer coefficients and subsequently, to define appropriate boundary conditions for FEM-based simulation. A comparison between the temperature distribution obtained from simulation and that measured in the experimental stand leads to the conclusion that numerical simulations carried out using COMSOL Multiphysics correctly depicted the heat transfer by conduction and natural convection. It was also found that the values of the heat transfer coefficient calculated using equations (4) and (2) agree well with the values determined from the experiments.

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