Journal of
MECHANICAL and ENERGY
ENGINEERING

ISSN: 2544-0780
Vol. 1 | No. 1(41) | June 2017
pp. 101-106

FLOW STRUCTURES DURING REFRIGERANTS CONDENSATION

Małgorzata SIKORA[1*]

[1*] Faculty of Mechanical Engineering, Department of Power Engineering, Koszalin University of Technology, Raclawicka 15-17, 75-620, Koszalin, Poland, e-mail: malgorzata.sikora@tu.koszalin.pl

(Received 30 March 2017, Accepted 15 May 2017)

Abstract: For several years, in the world are carried out studies on the refrigerants condensation in minichannels. These studies are aimed at understanding the condensation process and facilitate the design of mini heat exchangers. It is very important to optimize heat transfer and drive power consumption of the is the knowledge of the processes occurring during refrigerants condensation in pipe minichannels. It is important in this case to make a individual flow structures maps for the refrigerants, due to the significant effect of flow structured formed in the minichannel on the heat transfer and flow resistance. Unfortunately, in relation to the number of publications about condensation in minichannels, the number of published flow maps is relatively small. Due to the fact that the condensation process takes place differently in the minichannels and conventional channels, there is no possibility of using the flow maps for conventional channels to identification flow patterns in minichannels. One of the most popular flow maps for the condensation in minichannels is the map created by Colleman and Garimella, which was made for the R134a refrigerant. The authors conducted their own experimental studies of refrigerants R134a, R404A and R407C condensation in pipe minichannels with an internal diameter d = 3.3 - 0.31 mm. These studies results were subjected to calculation identification of flow structures using the map of Colleman and Garimella. These results are compared with the criteria published on Thome and Cavallini flow maps.

Keywords: condensation, refrigerants, minichannels, flow patterns

1. INTRODUCTION

Due to the development of new technologies for the miniaturization of power equipment (while increasing their efficiency), compact heat exchangers are studied around the world. Exchangers of this type are built from minichannels, which results in an increase of heat transfer intensity by a small surface. To the minichannels are qualified those channels which internal hydraulic diameter d_h < 3mm. Especially important are two-phase non-adiabatic flows, with accompanying phase change like in condensation or boiling.

Two-phase flow patterns in conventional channels in non-adiabatic conditions are completely different than those received in minichannels. Therefore, the uncritical transfer of the results obtained in the field of two-phase flow structures in conventional channels, to mini- and microchannels leads to highly falsified descriptions of thermal and flow phenomena. Similarly is in the case of adaptation of two-phase boiling flow maps to those occurring during condensation in small diameter channels.

It is known that in the small diameter channels significant impact on the mechanism of momentum and energy transport have viscosity and surface tension, while gravity and inertia forces are less important. In the work of Coleman and Garimella [5, 7] was found, for example, that for channels with a hydraulic diameter greater than 10 mm, the channel dimension and surface tension did not significantly influence the formation of two-phase flow patterns. Attempts were made to adapt two-phase flow structures maps for adiabatic conditions, with respect to flow with condensation. Example can be work of Łukaszuk [9, 10], where the adaptation of the Taitel and Dukler maps has been presented to experimental results of two-phase water vapor flow in a 2.5 mm hydraulic minichannel. The author stated that, for a limited range, the Taitel and Dukler map gives a satisfactory approximation to the experimental reasults in the recognition of two – phase structures boundaries. It has been stated that for diameters greater than 5 mm the structure recognition is slightly better, although there are noticeable shifts in these limits. Ewing et al. [6] investigated the structures of the adiabatic water-air mixture flow in a horizontal minichannel with an internal diameter of 1.6 mm. Attempts to capture the influence of surface tension on the structure and description of condensation in minicanoids were undertaken in the work of Tabatai and Faghri [12] and Akbar et al. [1]. These authors considered not only the influence of surface tension, but also the viscosity and wetting of the channel wall by the liquid phase. The tests were conducted in a rectangular channel with a hydraulic diameter of 1.4 mm, length 1130 mm, in the range G = 200 ÷ 1400 kg/(m^{2}s), for refrigerants R236ea, R134a and R410A. Coleman and Garimella proposed for the first time the classification of two-phase flow structures and their determinants. The presented works were devoted to the study of two-phase flow maps in circular, square and rectangular channels in the range of hydraulic diameter d_h = 1 ÷ 5 mm and mass flow density G = 150 ÷ 750 kg / (m^{2}s). Knowing the two-phase flow structures plays an important role in selecting the appropriate calculation correlation for the heat transfer coefficient and flow resistance. From a physical point of view, two-phase flow patterns have the following characteristics:

- bubbly - this is the structure of the gas phase (discontinuous vapor phase) distributed in the form of bubbles in the continuous liquid phase;
- plug – vapor bubbles can reach a size comparable to the diameter of the channel and move mostly at the top of its section;
- slug – with increasing flow velocity, the tangential stress on the surface of the phase separation causes an increase in the wave range by forming vapor bubbles along the flow in channel;
- intermittent – the liquid and gaseous phases are separated, generally with a smooth interface surface, usually at low speeds of both phases;
- wavy – when the velocity of the gas phase increases, disturbance occurs on the phase separation surface, waves are traveling along the flow direction;
- annular – a high velocity of the gas phase produces a vapor plugs and a liquid film is formed on the surface of the channel, the thickness of which is usually unsymmetrical with respect to the channel section and has a greater thickness in the bottom of channel.

In Fig.1 is shown a two-phase flow classification by Kawaji and Chung [8]

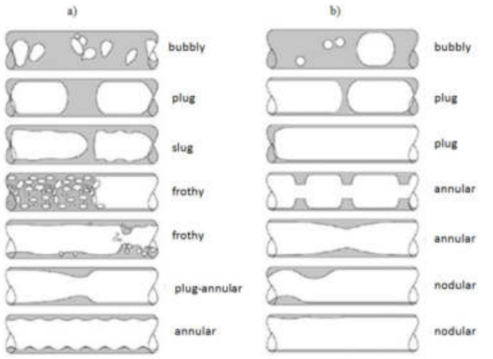

Fig. 1. Classification of two-phase flow by Kawaji and Chung [8] for: a) minichannels, b) microchannels

2. EKSPERIMENTAL REASULTS

Author attempted to identify two-phase flow structures under condensation conditions in minichannels using calculation and visualization methods. Due to the large database of own investigation results [3] and results of other authors it was possible to elaborate the calculation method and determine its effectiveness. For the HFE-7100 low-pressure refrigerant, in the lack of results in literature, own visualization studies were carried out in this field.

All calculation correlation for heat transfer coefficient and flow resistance shown by different authors are determined for the respective two-phase flow structure. Given the kind of the two-phase flow structure, it is important to determine the limits of its occurrence. Two-phase flow maps are used for this. It is known that in the two-phase flow there is a change of concentration of phases in time and space of probabilistic nature, which makes it very difficult to recognize them. Recognition of the energy and momentum transfer mechanism in two-phase flow, especially under non-adiabatic conditions (eg. during condensation of refrigerants) requires identifying the flow structures and their boundaries. The analysis of literature sources in this field indicates the two types of identification used in practice:

- “computational” identification - using two-phase flow maps prepared by other authors for different refrigerants, under different conditions of the condensation process,
- experimental identification - visualization of the flow and analyze of the resulting image.

2.1. Test stand

The schematic diagram of test stand for heat, flow and visualization investigations of HFE-7100 refrigerant condensation is shown in Figure 1. On the diagram of the test stand is specified two sections, named by the symbols A and B.

The schematic diagram of test stand for heat, flow and visualization investigations of HFE-7100 refrigerant condensation is shown in Figure 2. On the diagram of the test stand is specified two sections, named by the symbols A and B.

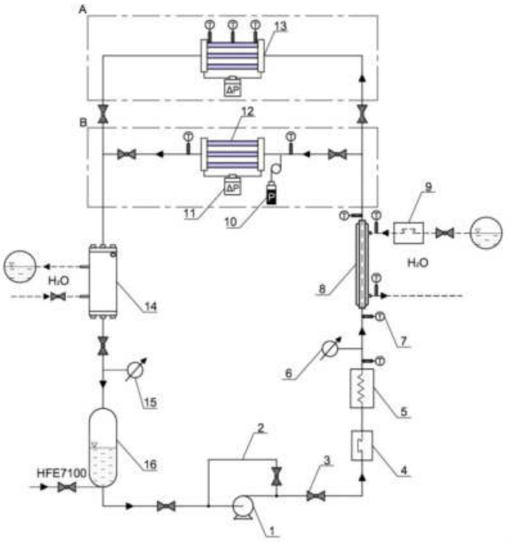

Fig. 2. Schematic of the test stand for thermal-flow and visualization of diabatic flow: A - Section for thermal and flow investigations, B - Section for experimental visualization of two-phase flow structures; 1 - ceramic pump, 2 – bypass for the flow control, 3 - valve, 4 – flowmeter for refrigerant, 5 - evaporator, 6 - manometer, 7 - K-type thermocouples, 8 - pre-heat exchanger "pipe in pipe" type , 9 - valve, 10 –flowmeter for cooling water, 11 – pressure sensor, 12 - differential pressure sensor, 14 - horizontal section for visualization, 15 - horizontal section of a heat-flow section 16 - valve, 17 - heat exchanger, 18 - vacuum pump, 19 - manometer, 20 – tank of liquid refrigerant HFE-7100

Section A was used in the heat and flow investigations of the HFE-7100 refrigerant condensing in pipe minichannels with an internal diameter of d = 2 mm. Research has been done to determine the experimental values of mean and local heat transfer coefficients and flow resistance during condensation. The B-section with measuring and recording instrumentation enabled visualization of the two-phase flow during HFE-7100 condensation in a minichannel, which was made as a glass tube (d = 2 mm, Fig.5). Section B measuring instrumentation allowed the observation of images of flow structures under the microscope (Fig.4b) and their recording by means of a camera (Fig.4a) coupled to the computer. In visualization studies, a stereoscopic microscope with a maximum range of magnification from 4.7x to 372x, was used. It is designed for observation in 150W halogen light and halogen illuminated 2 x 250W light. The i-SPEED camera is compatible with the microscope, with a max. recording speed 10000 fps and max. resolution 1280 x 1024 pix. The camera is equipped with 4GB of memory. It allows to measure of distance, speed and acceleration. The PC software for i-speed camera allows to control, analyze and edit recordings. The correct illumination of the investigated object allows two sets of reflected light equipped with a 2 × 250 W illuminator. Figure 3 shows the general view of the test stand. On Fig.5 is shown an investigated glass minichannel

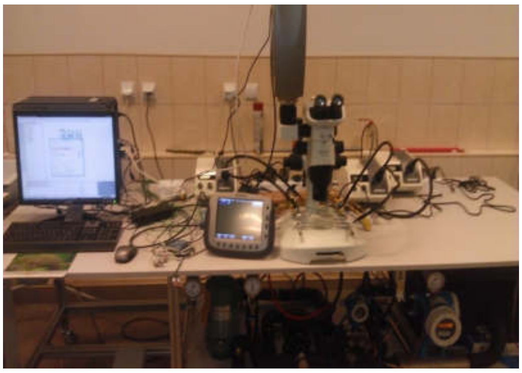

Fig. 3. Overall view of test stand

Fig. 4. Overall view of: a) i-SPEED camera, b) stereoscopic microscope

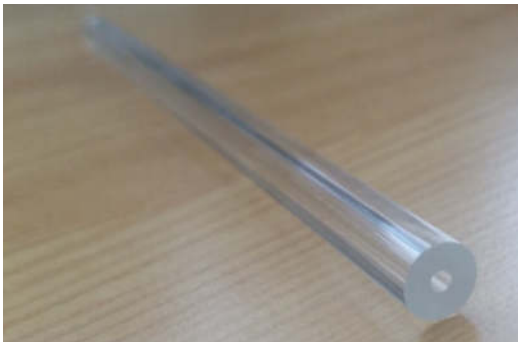

Fig. 5. Glass pipe mini channel with internal diameter $d_h = 2.0$ mm and length L = 15 cm

2.2. Experimental investigations results

Using own experimental data base witch the results of the R134a, R407C and R404A refrigerants condensation in pipe minichannels with internal diameter d = 0.31 ÷ 3.30 mm, a "computational" method of flow patterns identifying, was used. This method consists in comparing the results of experimental research with the results of calculations according to the criteria used by individual authors of two-phase flow structures maps. This required specifying the characteristic values describing the boundary conditions of the structures under experimental conditions. For the purpose of the analysis, the values of the apparent velocity of steam phase (gas) J_v and the Lockhart - Martinelli parameter χ_{tt} were determined according to the dependences:

$$J_v = \frac{G \cdot x}{\sqrt{g \cdot d \cdot \rho_v \cdot (\rho_l - \rho_v)}}, \quad , \tag{1}$$

$$\chi_{tt} = \left(\frac{1-x}{x}\right)^{0,9} \cdot \left(\frac{\rho_v}{\rho_l}\right)^{0,5} \cdot \left(\frac{\mu_l}{\mu_v}\right)^{0,1}, \tag{2}$$

where: G – mass flux density, x – vapor qality, g – gravity, d – internal diameter, ρ – density of : v – vapor, l – liquid, μ - viscosity of: v – vapor, l – liquid.

The occurrence range of individual flow patterns is also dependent on the vapor quality x and the mass flux density G. To identify the flow patterns, the results of experimental studies were put on flow maps published by such authors as Thome [13], Cavallini et al. [4] and Colleman and Garimella [5] (Figure 4 ÷ 6). It was found that in the range of the experimental investigation parameters were obtained: annular, annular-wave flow but plug or bubbly flow was obtained very rare. By practical use of different authors flow maps confirms the ambiguity of the occurrence of particular structures boundaries on these maps. Sometimes it is difficult to say in a clear way what structure are dealing with. In most cases, maps of this type have been developed for R134a refrigerant, which is the best studied factor among freons replacers.

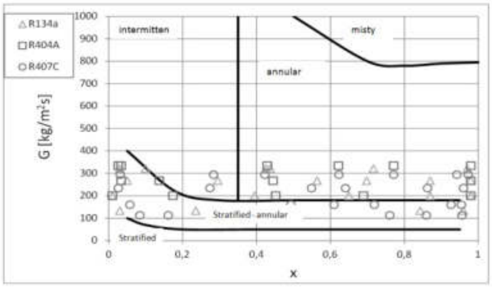

Fig. 6. The structure map of two-phase flow by Thome [13] with experimental investigation results of R134a, R404A and R407C refrigerants condensation in minichannel with internal diameter $d_h = 2,3$ mm

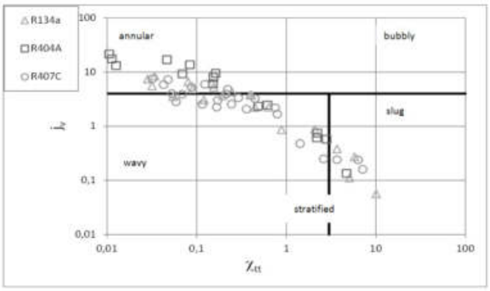

Fig. 7. Fig.5. The structure map of two-phase flow by Cavallini [4] with experimental investigation results of R134a, R404A and R407C refrigerants condensation in minichannel with internal diameter $d_h = 2.3$ mm

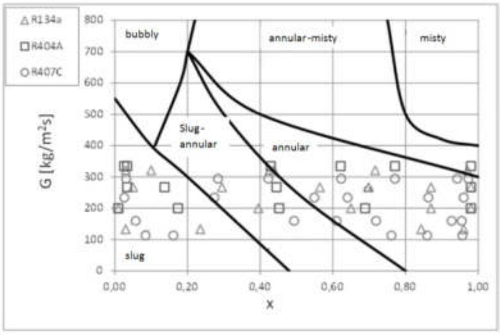

Fig. 8. The structure map of two-phase flow by Colleman and Garimella [5] with experimental investigation results of R134a, R404A and R407C refrigerants condensation in minichannel with internal diameter $d_h = 2.3$ mm

2.3. Visualization results of HFE7100 condensation in minichannel

Experimental studies of two – phase flow visualization during refrigerant HFE-7100 condensation were carried out at the test bench (Figure 2) in section B, using a pipe minichannel which an internal diameter of $d_h = 2$ mm made of glass. The visualization conditions allowed to show the flow patterns of condensation in a top view (Fig.7). Figure 8 shows a description of the elements of the image seen in the microscope and recorded by the camera.

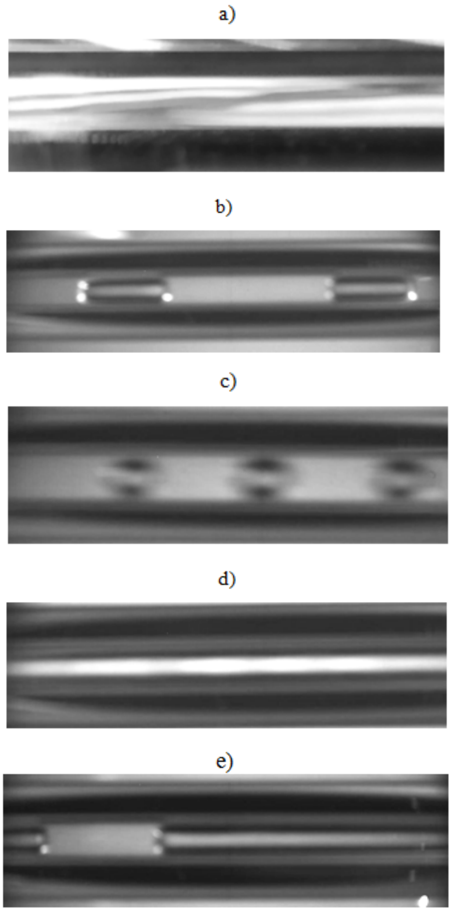

Fig. 9. Observed two-phase flow structures during HFE-7100 refrigerant condensation in minichannel with internal diameter d = 2 mm: a) wavy – T_s = 81°C, G = 80 kg/(m^{2}s), x = 0,62; b) plug - T_s = 83°C, G = 56 kg/(m^{2}s), x = 0,40; c) bubbly - T_s = 63°C, G = 162 kg/(m^{2}s), x = 0,30; d) annular - wavy, T_s = 76°C, G = 91 kg/(m^{2}s), x = 0,69; e) plug - T_s = 53°C, G = 192 kg/(m^{2}s), x = 0,54;

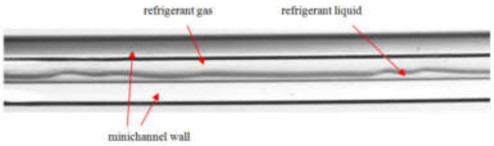

Fig. 10. Auxiliary description of the two-phase flow pattern image during the condensation of the HFE-7100 refrigerant in pipe minichannel with internal diameter d_h = 2 mm

The obtained images of the flow structures were subjected to computer image analysis to determine the void fraction on the basis of dependence:

$$\varphi = \frac{V_v}{V_l+V_v}, \qquad (3)$$

where: V_v – volume of the vapor phase, V_l– volume of the liquid phase.(2).

To determine the void fraction from the image, the ratio of the fields occupied by the gas to the total cross-sectional area of the visible channel is determined. This is possible assuming that in a circular tube, the flow patterns are circularly symmetrical. In this way, it can be assumed that the proportion of the gas phase in the total volume determined for the two-dimensional image is close to the actual proportion, and that the static void fraction [2] is set. The author presented in the present study a method witch using an algorithm developed in MATLAB using the method described in [11]. To determine the static fill rate φ cut the image of the channel content from the image and then change its structure to binary. Figure 9 shows the steps for image processing. The algorithm calculate black and white pixels from image.

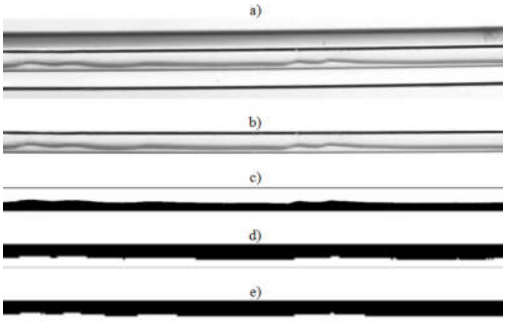

Fig. 11. Next steps of image processing before image analysis: a) film cage, b) image after cutting minichannel interior, c) binary image, d) image after color inversion by algorithm, e) image filtered by algorithm

If the void fraction is known from the image, it is possible to calculate vapor quality, what minimizes the error of its designation.

3. CONCLUSIONS

In summarizing the experimental results of visualization studies of HFE-7100 refrigerant condensation structures, found that:

1. The low-pressure refrigerant HFE-7100 has the advantage of modeling two-phase flow structures under condensation conditions in flow in tubular minichannels.
2. In the field of visualization tests, the following structures appeared in the condensation conditions: plug, wave, annular and annular-wave structures.
3. With condensation parameters occurring in mini compact heat exangers, annular and annular-wave structures are most common.
4. Visualization studies have demonstrated the possibility of further systematic studies of two-phase flow structures allowing the attempt to generalize

maps of two-phase flow structures condensed not only for HFE-7100 and other low pressure factors. It is anticipated that these studies will be completed in the near future.

5. To determine void fraction and vapor quality can be used computer image analysis. This kind of analysis can be use to determine the velocity of the phase and the geometrical parameters of the flow patterns.

Nomenclature

Symbols

d_h – hydraulic internal diameter, m
x – vapor quality
φ – void fraction
g – acceleration, m/s^2
ρ_l – density of the liquid, kg/m^3
ρ_v – density of the vapor, kg/m^3
μ_l – viscosity of the liquid, Pa·s
μ_v – viscosity of the vapor, Pa·s
X_{tt} – Lockhart - Martinelli parameter
J_v – apparent velocity of gas
G – mass flux density, kg/m^{2}s
L – length of minichannel, m
T_s – saturation temperature, °C
V_l – volume of liquid phase, m^3
V_v – volume of vapor phase, m^3

References

1. Akbar M.K.: Plummer R.D., Ghiaasiaan A. (2003): On gas liquid two-phase flow regimes in microchannels. *Int. J. of Multiphase Flow*, vol. 29, pp.855-865.
2. Bohdal T. (2003): Pomiary stopnia zapełnienia czynnika chłodniczego w kanale. *Chłodnictwo*, No 1, 14-19.
3. Bohdal T., Charun H., Sikora M. (2011): Comparative investigation of the condensation of R134a and R404A refrigerants in pipe minichannels. *Int. J. of Heat and Mass Transfer*, vol. 54, pp. 1963-1974.
4. Cavallini A., Del Col D., Doretti L., Matkovic M., Rossetto L., Zilio C. (2005): Two-Phase Frictional Pressure Gradient of R236ea, R134a and R410A inside Multi-Port Mini-Channels. *Experimental Thermal and Fluid Science,* vol. 29, pp. 861-870.
5. Coleman J., Garimella S. (2003): Two-Phase Flow Regimes in Round, Square and Rectangular Tubes During Condensation of Refrigerant R134a. *Int. J. of Refrigeration*, vol. 26(1), pp. 117-128.
6. Ewing M.E., Weinandy J.J., Christensen R,.N. (1999): Observations of two-phase flow patterns in a horizontal circular channel. *Heat Transfer Engineering*, vol. 20 (1), pp. 9-14.
7. Garimella S. (2004): Condensation flow mechanisms in microchannels: basis for pressure drop and heat transfer models. *Heat Trans. Eng.*, vol. 25(3), pp. 104-116. [6]
8. Kawaji M., Chung M. (2004): Adiabatic gas–liquid flow in microchannels. *Microscale Thermophysical Engineering*, 8, 239–257.
9. Łukaszuk M. (2005): Zastosowanie wykresu Taitela i Dublera do identyfikacji struktur przepływów dwufazowych w kanałach o małych średnicach. *Materiały XIX Zjazdu Termodynamików*, Sopot.
10. Łukaszuk M. (2010): Experimental investigation of two-phase steam flux In horizontal channels of small diameter. *Heat Transfer Engineering*, vol. 31 (4), pp. 331-334.
11. Michalska-Pożoga I., Tomkowski R., Rydzkowski T., Vijay Kumar Thakur (2016): Towards the usage of image analysis technique to measure particles size and composition in wood-polymer composites. *Indus-trial Crops and Products* , 92, 149-156.
12. Tabatabai A., Faghri A. (2001): A new two-phase flow map and transition boundary accounting for surface tension effects in horizontal miniature and micro tubes. *J. of Heat Transfer*, vol. 123, pp. 958-968.
13. Thome J.R. (2004-2008): *Engineering Data Book III*: Chapter 8 – Condensation inside tubes. Wolverine Tube, Inc.

Biographical note

Małgorzata Sikora received her M.Sc. degree in Environmental Engineering (specialization: Heating and air conditioning) and next Ph.D (with honors) as well as D.Sc. degree in Machinery Construction and Operation from Koszalin University of Technology, in 2008 and 2011 respectively. Since 2011 she has been an assistant in the Department of Heating and Refrigeration Engineering at the Koszalin University of Technology. Currently she works as an assistant professor in Department of Power Engineering. Her scientific interests concern a heat and flow phenomenon during refrigerants condensation, refrigeration, heat pumps, etc. She has participated a in 4 national research projects, 1 international education project (Tempus Energy). She presenting results of her work at 4 international and numerous national conferences, she published 4 articles in journals from the Philadelphia list (LIST A) and 15 articles in national magazines (LIST B) and 46 papers printed in national and international conferences materials. Dr. Eng. Małgorzata Sikora is also co-author of 1 monograph published in English, and 1 didactic textbook.