Centrum Rzeczoznawstwa Budowlanego

Open Access Journal
Modern Engineering 1 (2022) 20-35
journal homepage: https://mengineering.eu/

MODERN ENGINEERING

Approximation of flow characteristics of steam traps based on experimental research

Paweł ZIEMIAŃSKI [1], Andrzej GRZEBIELEC*[1], Adam SZELĄGOWSKI[1], Mateusz ŚMIECHOWICZ[2]

[1]Warsaw University of Technology, Faculty of Power and Aeronautical Engineering, Institute of Heat Engineering, Warsaw, Poland
[2]Eneon sp. z o. o., Warsaw, Poland

Abstract

This study aimed to approximate the operating characteristics of steam traps through experimental research and mathematical analysis. The research presented the phenomena leading to the development of steam traps, their relevance to power engineering and production plants, and the energy properties of water vapor for heat transport and exchange. The study also discusses problems that can occur in steam systems and how steam traps can prevent adverse phenomena. The experimental studies allowed the researchers to determine the operating characteristics of steam traps, and mathematical analysis extended the results to other cases.

Keywords: steam traps, experimental study, energy efficiency

1 Introduction

Water vapor is widely used in various industries, thanks to its unique properties. Its primary use is as an energy carrier, with power plants and combined heat and power plants being among the most important industries where steam plays a crucial role. Water vapor facilitates the conversion of chemical energy from fuels such as hard coal, lignite, or biomass into electricity. Steam drives the turbine in such cycles, which in turn produces mechanical energy that is later converted into electrical energy by the generator. Another important use of steam in industry is as a heat carrier. The ability of water vapor to transfer large amounts of heat relative to its small mass makes it an attractive choice for this purpose. Water vapor is produced by the evaporation of water, a low-cost and easily accessible material that has minimal negative impact on the environment. This sets it apart from other substances that could potentially be suitable for similar applications.

1.1 The usage of steam in steam systems

The reverse process to the process of water evaporation is condensation, which occurs in devices that receive heat from steam for production processes or heating purposes. Such devices include heat exchangers, distillers, air heaters, autoclaves, presses, etc., where the heat contained in the steam is primarily utilized. [24]. Analyzing Figure 1, it can be seen that the greatest amount of heat is possible to receive from the transformation of saturated dry steam into boiling water. Another parameter that is worthy of mention in this process is the very high heat transfer coefficient, which results in a significant reduction in the area required for heat transfer. Further analysis of the diagram shown in Figure 3, it can be seen that the amount of heat received in the process of cooling of boiling water, as well as cooling the steam superheated to the temperature of saturated dry steam, is much smaller. It should be noted that the heat transfer coefficient for saturated dry steam is 1160 W/(m^2·K), it is much higher than the heat transfer coefficients for water – 400 W/(m^2·K) and superheated steam 90 W/(m^2·K). It follows that for the transfer of the same amount of

* **Corresponding author:** E-mail address: (andrzej.grzebielec@pw.edu.pl) Andrzej GRZEBIELEC

Received 1 January 2022
Available online 15 March 2022
ISSN 2450-5501
Published by Centrum Rzeczoznawstwa Budowlanego

heat for the process of condensation of saturated dry vapor, a much smaller surface area will be needed than in other processes.

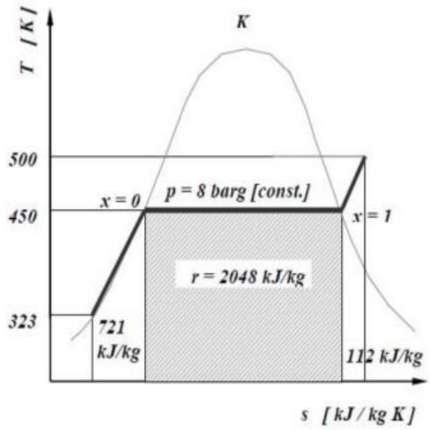

Figure 1. The amount of energy involved in the phase change process for steam [24].

Upon close examination of the Fig. 1., it is apparent that the largest amount of energy is transferred during the condensation process of saturated dry vapor, relative to the mass involved in the process.

1.2 Purpose of using steam traps

Water vapor is formed when water evaporates into a gas phase. For this process to occur, water molecules must possess enough energy to break the bonds between molecules, such as hydrogen bonds. The energy required to convert a liquid into a gas is known as the heat of evaporation. Steam-based heating processes utilize the heat of evaporation and transfer it to the object. Once the condensation process is complete, the steam releases its heat of evaporation and becomes a condensate. In other words, unlike fresh steam, condensate lacks the ability to perform work [6]. Therefore, the heating efficiency decreases if the condensate is not promptly removed, whether in the steam transport lines or in the heat exchanger.

2 Experimental research

Fig. 2 shows a view of the test bench used to carry out measurements during experimental research, while Fig. 3 presents a photograph. The test stand for steam traps consisted of several elements, including a condensate pump (11), flow meter (1), two single-phase electric heaters with a capacity of 2 kW each, one three-phase electric heater with a capacity of 3 kW (2), filter (3), pressure transducers (4 and 7), temperature sensors (5 and 8), steam trap (6), condensate cooler (9), condensate tank (10), and close valve (12). The heater capacity was regulated by a control system connected to a PC, which adjusted the heater power by changing the ratio of the time of switching on and disconnecting the heater in the cycle to obtain the required condensate supercooling for testing. Water was pumped by means of a pump, and as it flowed through the pipes in the location of the heaters, it warmed up. The *T1* and *P1* sensors measured the temperature and pressure of the condensate, respectively, just before the steam trap. Before the dehydrator, the condensate passed through a strainer to capture any contaminants, which is crucial for the tested type of traps with small nozzle diameters. The condensate then passed through a nozzle dehydrator, where there was a decrease in pressure and temperature. The *T2* temperature and *P2* pressure sensors located behind the dehydrator allowed for the determination of any changes in these parameters. The condensate then went through a dry cooler, consisting of a finned heat exchanger and a fan, to cool the very hot condensate flowing out of the dehydrator. The intensity of the dry cooler could be adjusted by changing the fan power. After passing through the cooler, the dry condensate went into the condensate tank. The entire pipe string, from the location of the first heater to the dehydrator, was insulated with glass wool to prevent excessive heat loss and achieve small condensate supercooling values as well as a steady state. All connections of individual elements building the test stand were carried out by twisting and sealed with Teflon tape to ensure system tightness. The condensate circulation was repeated, with the condensate sucked into the pump from the condensate tank. Atmospheric pressure was present in the tank because it was an open tank. This resulted in less external influence on the condensate parameters.

The regulation of the tested condensate pressure before the trap was carried out by changing the closing of the bleed valve located just after the outlet from the pump. A kind of "bypass" was used, which allowed part of the pumped water stream to bypass the pipeline with the tested dehydrator, and thus affect the change in condensate pressure in the measuring part of the system. The maximum water overpressure that could be achieved with the pump used was 9 bar, and the maximum condensate flow was 3.3 m^3/h. All pressure and temperature readings were carried out using the Siemens Simatic HMI controller. The workstation program was created in the TIA Portal environment. The results obtained in this way were presented on a display (Figure 32) integrated into the controller system. With the help of this controller, the power of the dry cooler fan was also adjusted. This was done through a signal in the range of 0-10 V. In the original version of the test bench, this controller was also used to regulate the pump power and carried out the flow reading from the magnetic water meter.

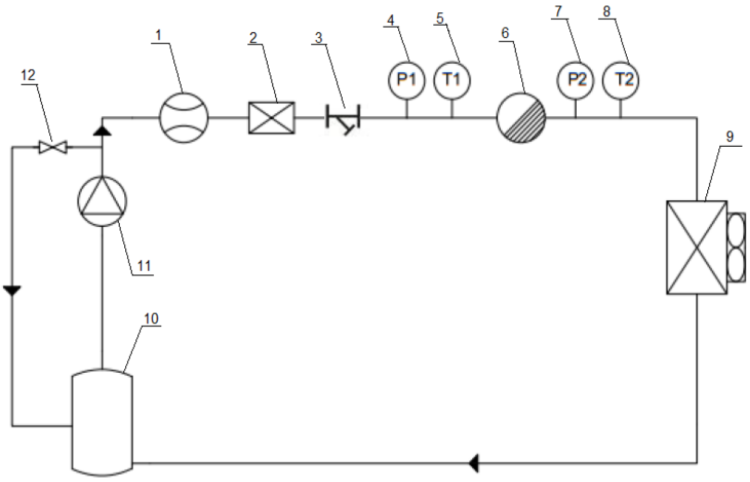

Figure 2. Experimental setup

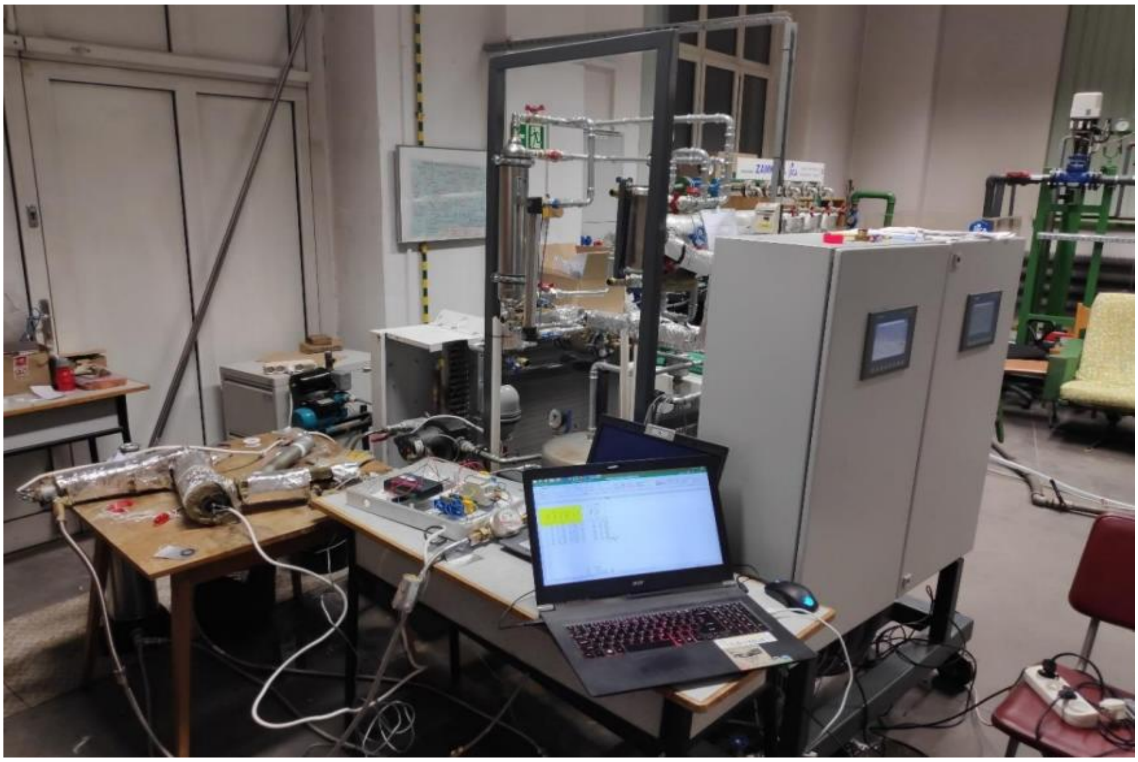

Figure 3. Experimental setup view

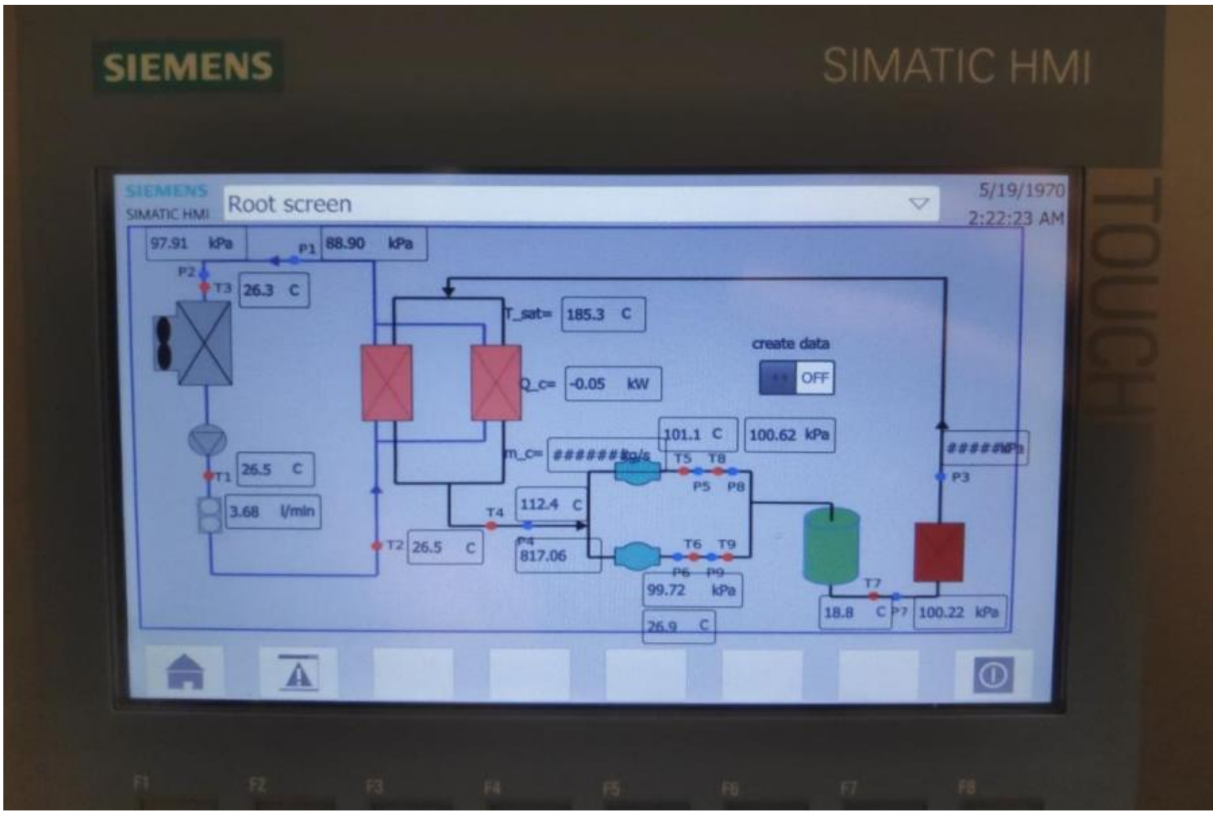

Figure 4. Control panel view

2.1 Experimental results

The type of steam traps tested were steam traps with a nozzle. The dimensions characteristic for this type of traps are the dimensions of the nozzle diameter D and the drilling depth L. According to scientific studies [14] [22], it is these dimensions that significantly affect the nature of the two-phase flow in the dehydrator. The driers supplied by the manufacturer were described by the values of diameter D and drilling lengths L. After noticing the occurrence of frequent inconsistencies during the analysis of measurement results, it was decided to verify the size of diameter D using a microscope. The measurements showed that in many cases the diameter D declared by the manufacturer did not comply with the measured value. Therefore, Table 1 shows the diameters of the nozzle diameters of the test driers declared by the manufacturer and the actual ones measured under a microscope.

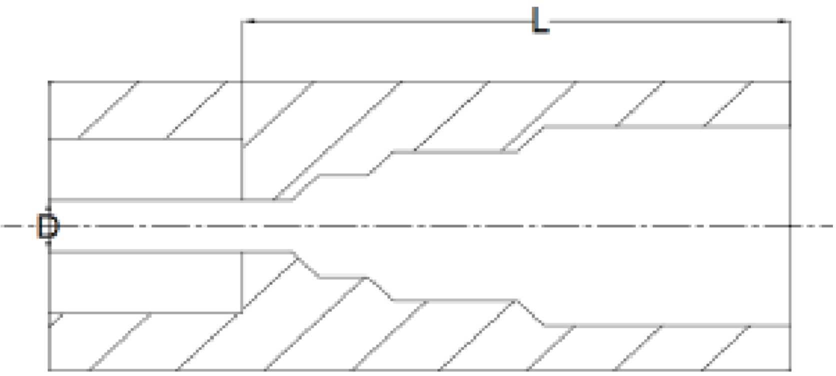

Figure 5. Cross-section of the examined steam traps

Table 1. Steam traps dimensions

Designation	Declared diameter	Measured diameter	drilling depth	flow surface
	mm	mm	mm	mm^2
040-6469	0.39	0,51	64.69	0.83
060-6021	0.60	0.47	60.21	0.69
080-6427	0.80	0.97	64.27	3.05
060-6000	0.60	0.60	-	1.13
067-6000	0.67	0.67	-	1.41

2.2 Measurement methodology

The mass flow of condensate was tested depending on its supercooling [1] for different pressure values prevailing in the system before the dehydrator. Steam traps on the test bench were tested as follows: At the very beginning, before each measurement cycle, the SIMENS SIMATIC HMI controller was activated to take the readings obtained during the tests, and then:

1. The water circulation pump was started.
2. The heaters were turned on.
3. The tested water pressure was set by means of a bleed valve control at the pump.
4. The measuring supercooling temperature was set by means of heater power regulation.
5. The steady state of the system was expected – no temperature increase before the dehydrator.
6. The results of the measurements were read.
7. The tested pressure was changed and a new measuring temperature was set.

Measurements were made for supercooling from approx. 10 K to 150 K for pressures from 300 to 800 kPa. The change in the test pressure setting was carried out by changing the opening degree of the bleed valve located just behind the pump. The regulation of the tested supercooling was carried out by changing the switching time of a three-phase heater with a power of 3kW. This adjustment was carried out by means of a computer program and a simple control system. The other two heaters with a power of 2kW each, were switched on with full power if required by a given measurement series. The volumetric flow reading was made using a water meter. Then, after determining the density of water for given temperature and pressure conditions, the volume flux was converted into a mass flux.

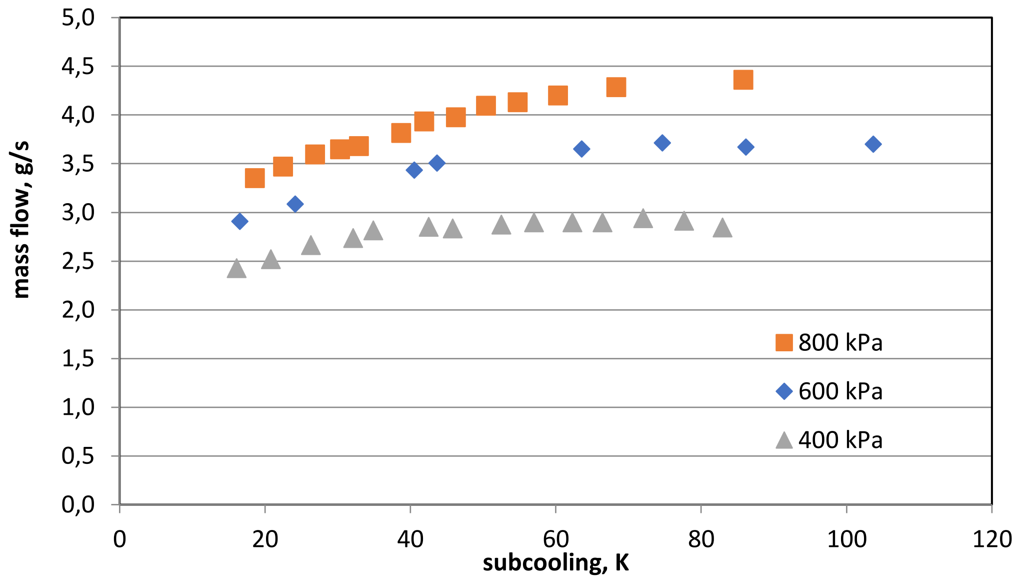

Figure 6. Mass flow of condensate as a function of subcooling value for a steam trap (nozzle diameter D=0.47 mm)

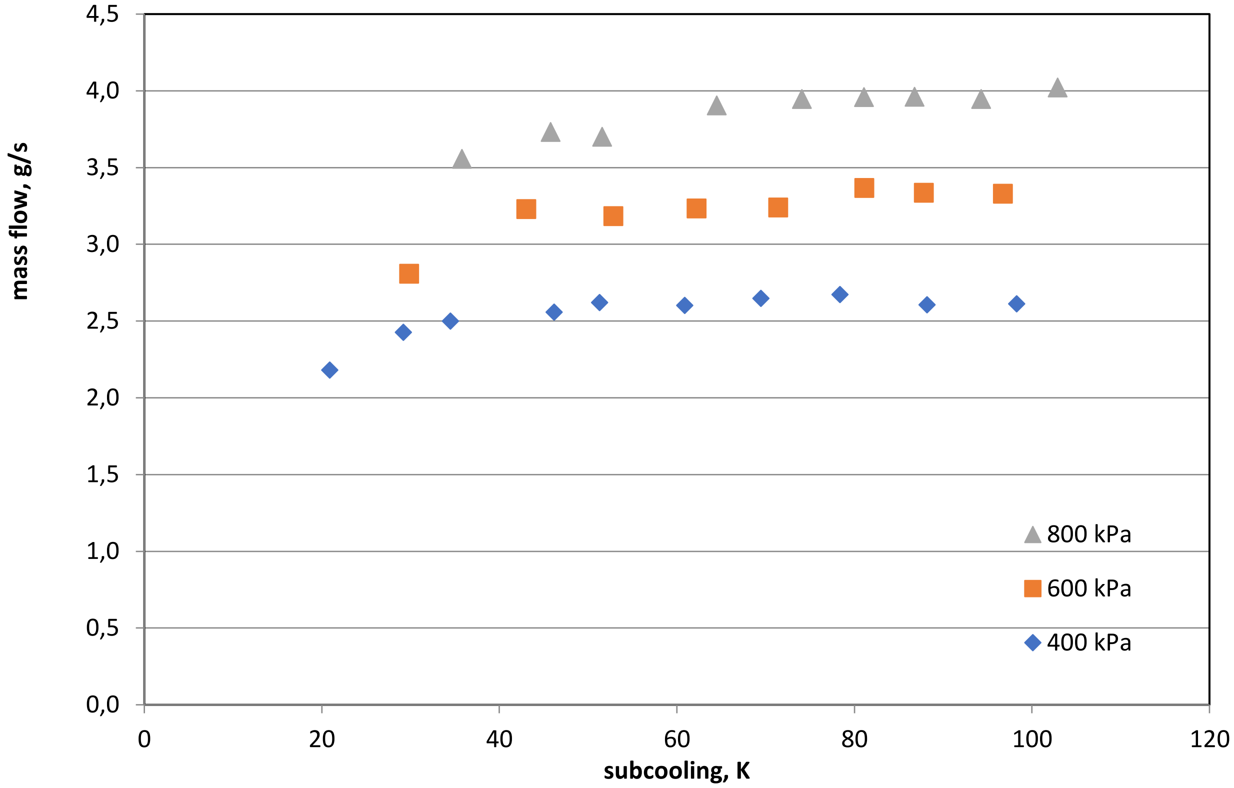

Figure 7. Mass flow of condensate as a function of subcooling value
for a steam trap (nozzle diameter D=0.51 mm)

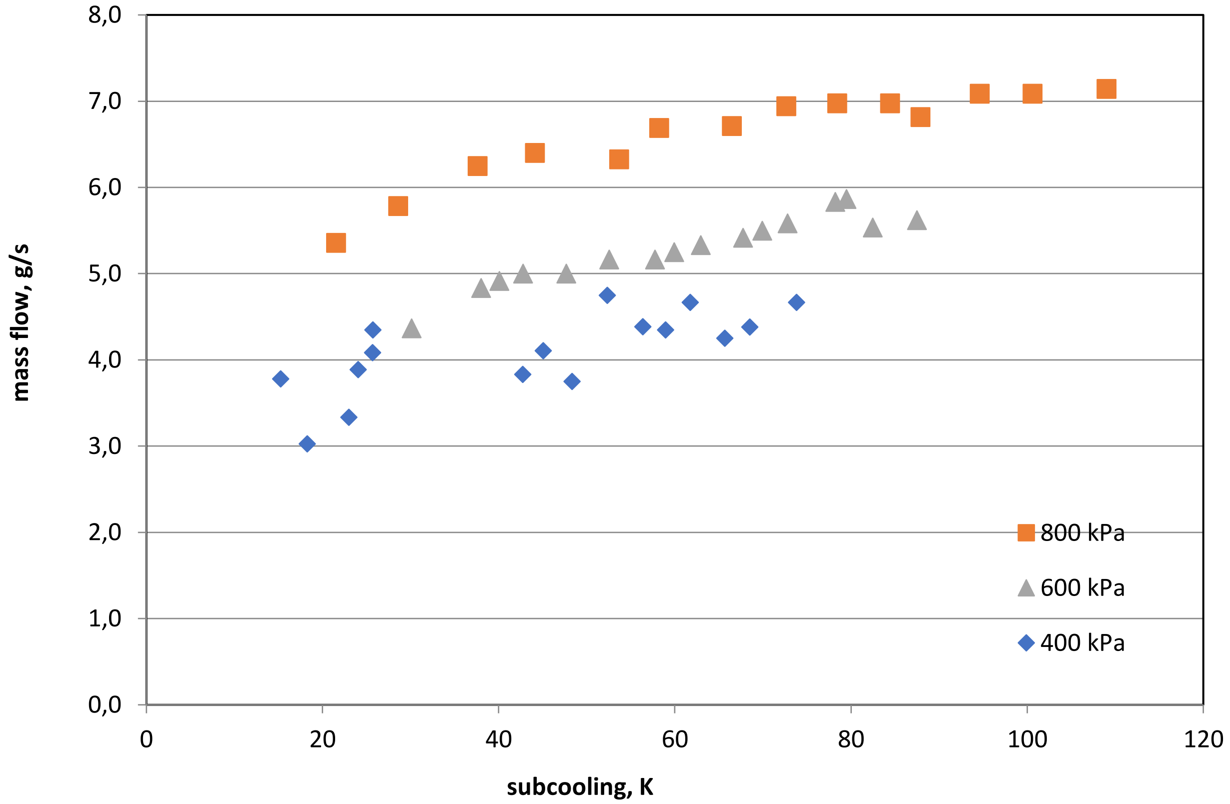

Figure 8. Mass flow of condensate as a function of subcooling value
for a steam trap (nozzle diameter D=0.60 mm)

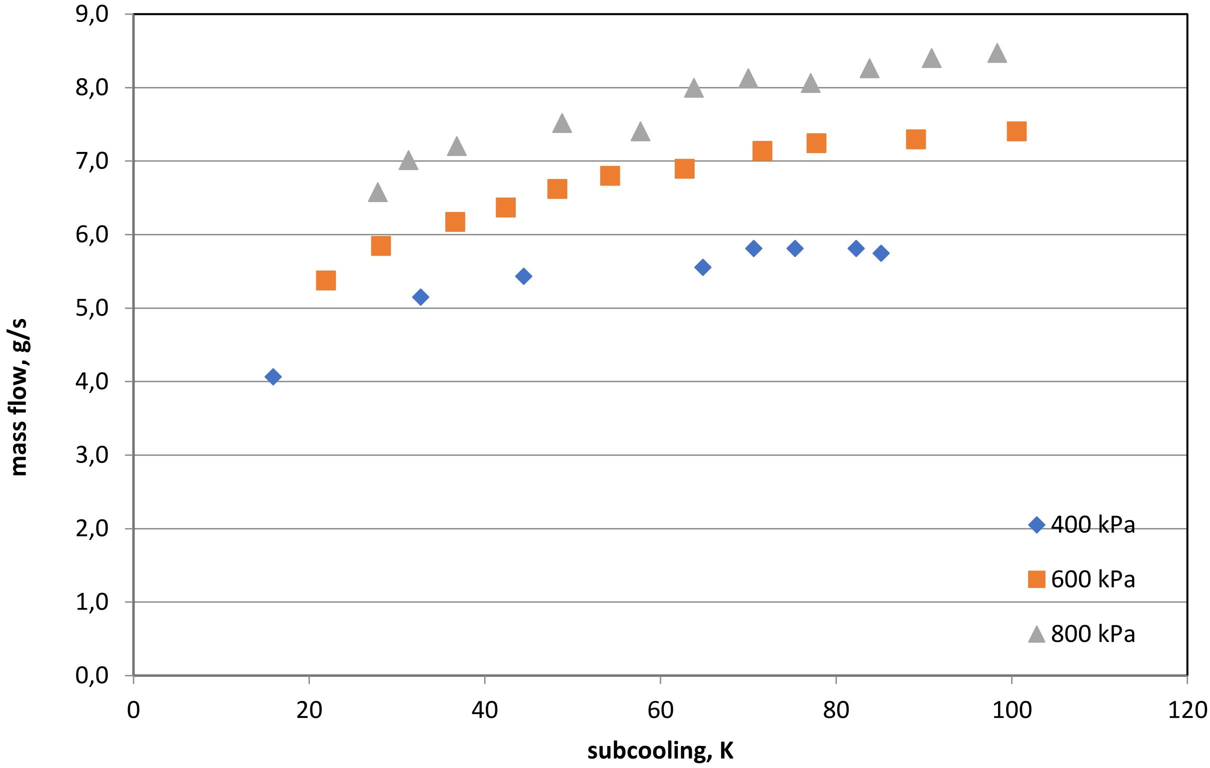

Figure 9. Mass flow of condensate as a function of subcooling value
for a steam trap (nozzle diameter D=0.67 mm)

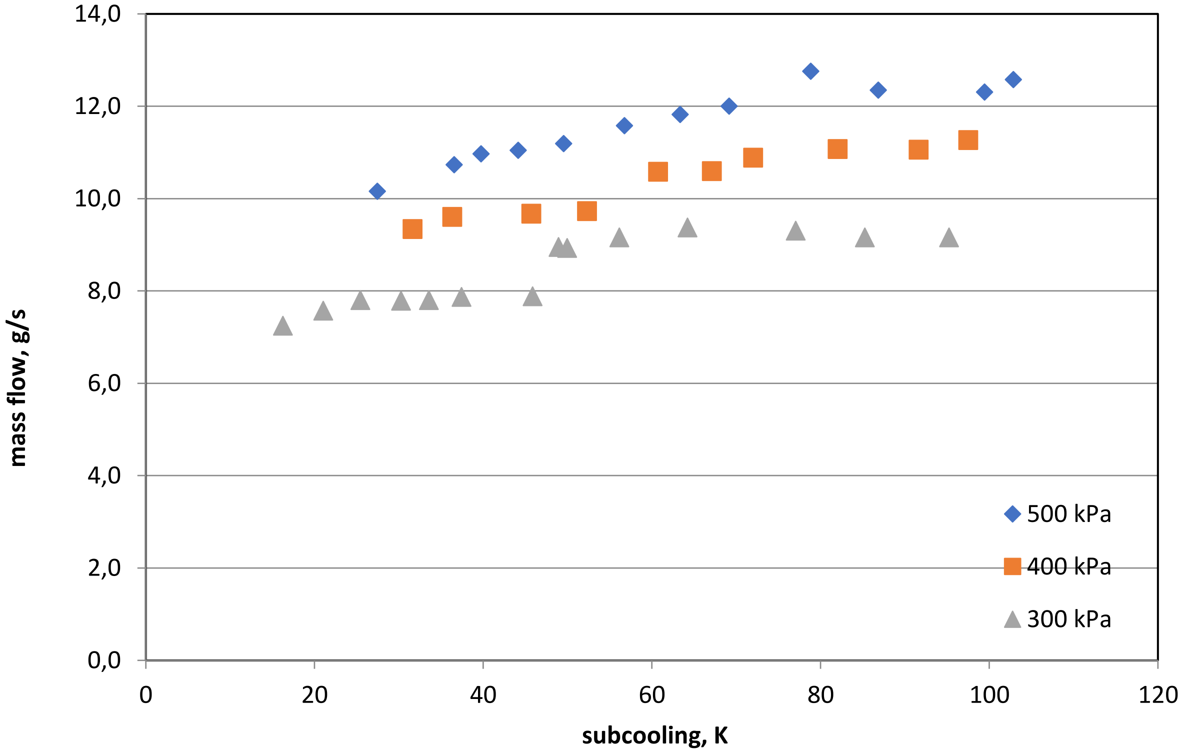

Figure 10. Mass flow of condensate as a function of subcooling value
for a steam trap (nozzle diameter D=0.97 mm)

3 Approximation of steam traps flow characteristics

Presentation of the approximation issue In broadly understood technical sciences, a very important element is to conduct research. These tests often consist in measurements of pairs of quantities, which, as it is assumed, are related to each other by some functional relationship, e.g. the velocity of the medium flow depending on the prevailing pressure or the deflection of the material depending on the applied force. If, on the basis of a series of points obtained from these measurements plotted on the coordinate system described by the measured quantities, it is possible to notice any tendency of these points to arrange, then a very appropriate action in such a situation is to find a curve that approximates as accurately as possible the location of points with values measured experimentally. And it is precisely the problem of finding such curves that approximation theory deals with [9]. Presenting the problem in more scientific language; The values are the values of the unknown function f (x) in points x0, x1 ... xn (approximation nodes) and the function F(x) is sought, which in the approximation nodes takes values close to the function f (x) , and at other points approximates it as well as possible. Approximation theory focuses on two types of problems. The first of these is the aforementioned problem of adjusting the curves as accurately as possible to the pairs of points obtained as a result of experimental research. The second type of problem is looking for a simpler function, based on the more complicated one that is known. This simpler function still needs to run as close as possible to the points resulting from the dependency contained in the more complex function.

There are various approximation methods [15], these are m.in.:

- mean quadratic approximation,
- linear approximation,
- uniform approximation,
- polynomial approximation.

The method [8] used to approximate the results obtained on the basis of experimental studies in this research work will be presented. After graphical analysis of the distribution of points on the coordinate system described by relationships measured experimentally (mass flow from condensate supercooling), the chosen method is approximation of the second degree polynomial. Here are the mathematical relationships describing this method: General formula of a polynomial of the second degree:

$$\mathrm{y(x)} = a_0 + a_1 x + a_2 x^2 \tag{1}$$

The search for parameters of such a polynomial (a_0, a_1, a_2) that passes as close as possible to all points determined experimentally (xi, yi) consists in minimizing the following sum:

$$S(a_0, a_1, a_2) = \sum_{i=1}^{n} (y_i - a_0 - a_1 x_i - a_2 {x_i}^2)^2 \tag{2}$$

From the system of equations:

$$\frac{\partial S(a_0, a_1, a_2)}{\partial a_0} = 2\sum_{i=1}^{n} (y_i - a_0 - a_1 x_i - a_2 {x_i}^2)\,(-1) = 0 \tag{3}$$

$$\frac{\partial S(a_0, a_1, a_2)}{\partial a_1} = 2\sum_{i=1}^{n} (y_i - a_0 - a_1 x_i - a_2 {x_i}^2)\,(-x_i) = 0 \tag{4}$$

$$\frac{\partial S(a_0, a_1, a_2)}{\partial a_2} = 2\sum_{i=1}^{n} (y_i - a_0 - a_1 x_i - a_2 {x_i}^2)\,(-{x_i}^2) = 0 \tag{5}$$

After transformations:

$$a_0 n + a_1 \sum_{i=1}^{n} x_i + a_2 \sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} y_i \tag{6}$$

$$a_0 \sum_{i=1}^{n} x_i + a_1 \sum_{i=1}^{n} x_i^2 + a_2 \sum_{i=1}^{n} x_i^3 = \sum_{i=1}^{n} x_i y_i \tag{7}$$

$$a_0 \sum_{i=1}^{n} x_i^2 + a_1 \sum_{i=1}^{n} x_i^3 + a_2 \sum_{i=1}^{n} x_i^4 = \sum_{i=1}^{n} x_i^2 y_i \tag{8}$$

Systems of normal equations are systems of linear equations in which the unknowns are: a_0, a_1, a_2.

By approximating with a polynomial of the second degree pairs of the size of the mass flow stream of condensate and supercooling for the tested pressures and steam traps with different nozzle diameters, the following results were obtained. They are presented in graphic form.

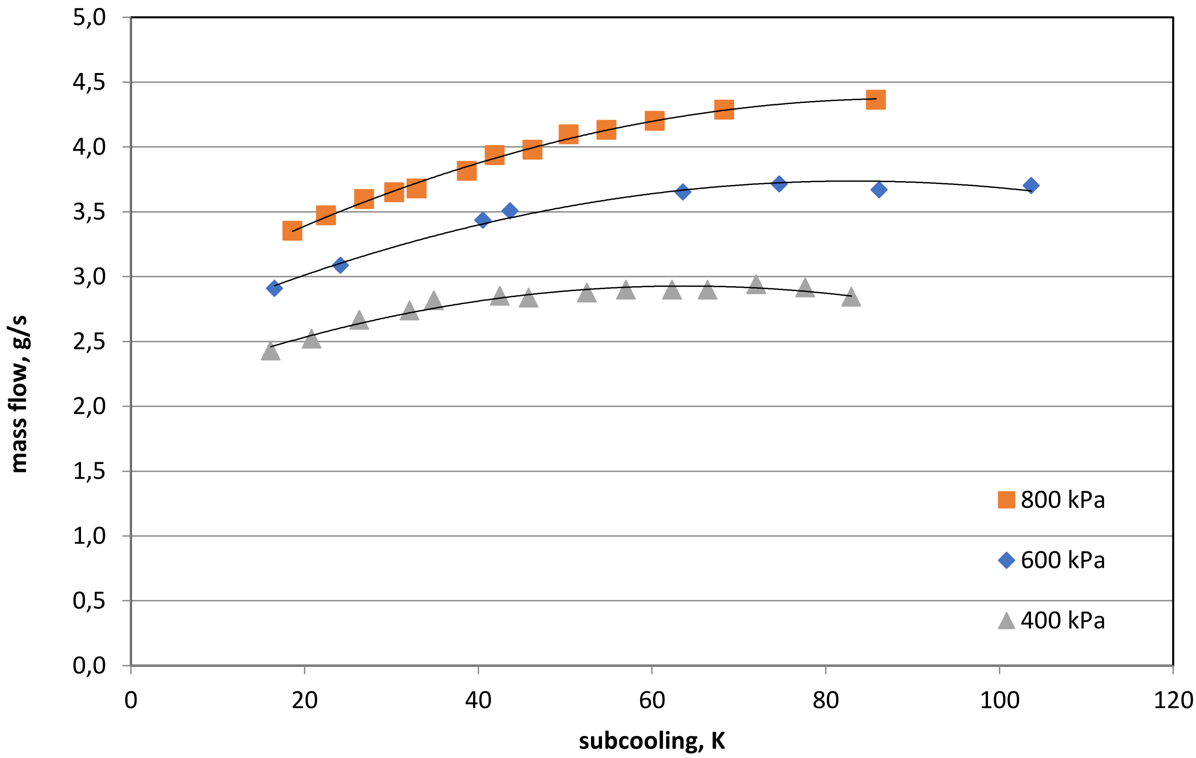

Figure 11. Approximation of operating characteristics of steam traps with nozzle diameter D=0.47mm

- Approximating polynomial equation for a series of measurements for 400 kPa:

$$y = -0.0002x^2 + 0.0264x + 2.0873$$

- Approximating polynomial equation for a series of measurements for 600 kPa:

$$y = -0.0002x^2 + 0.0302x + 2.4798$$

- Approximating polynomial equation for a series of measurements for 800 kPa:

$$y = -0.0002x^2 + 0.0366x + 2.7403$$

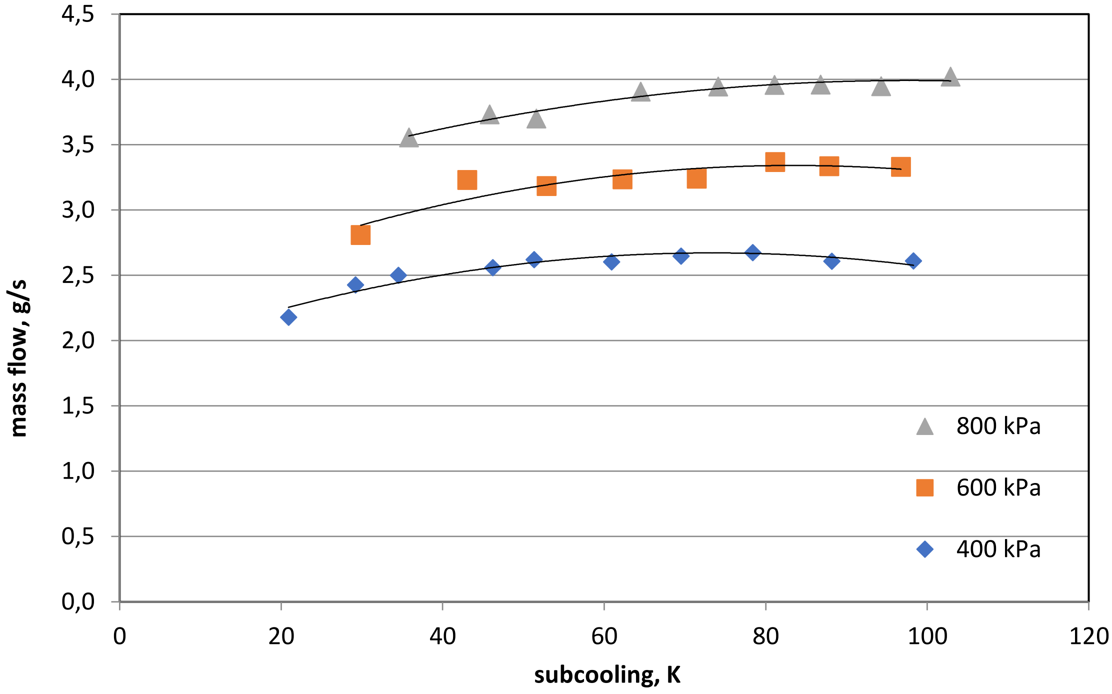

Figure 12. Approximation of operating characteristics of steam traps with nozzle diameter D=0.51mm

Approximating polynomial equation for a series of measurements for 400 kPa:

$$y = -0.0002x^2 + 0.0222x + 1.8569$$

Approximating polynomial equation for a series of measurements for 600 kPa:

$$y = -0.0002x^2 + 0.0266x + 2.2323$$

Approximating polynomial equation for a series of measurements for 800 kPa:

$$y = -0.0001x^2 + 0.0216x + 2.9352$$

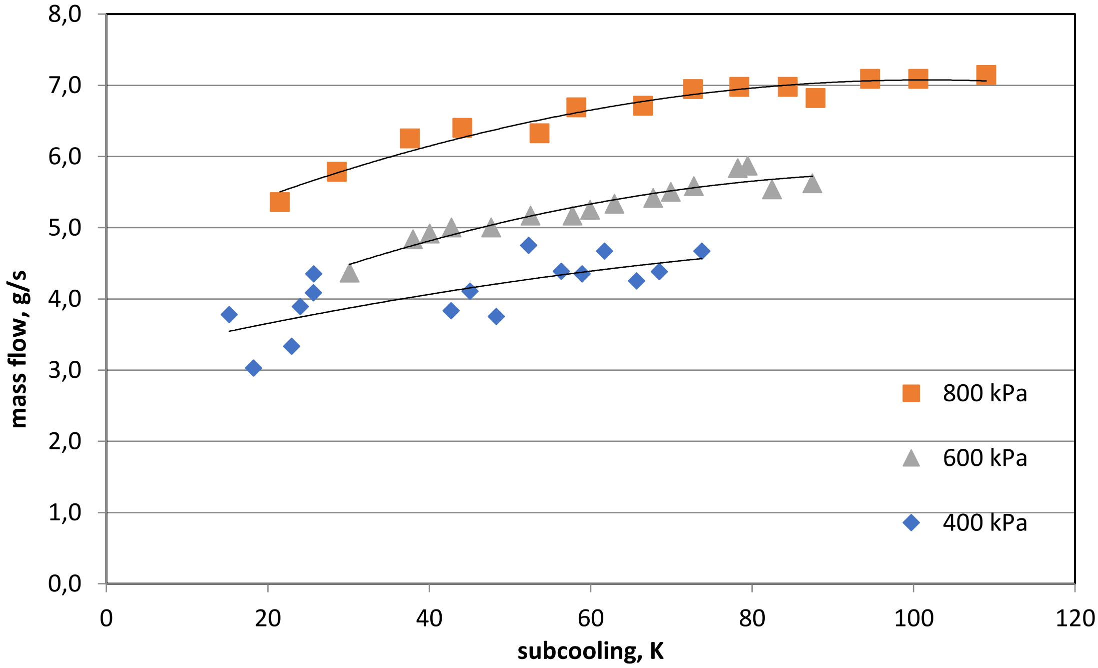

Figure 13. Approximation of operating characteristics of steam traps with nozzle diameter D=0.60mm

Approximating polynomial equation for a series of measurements for 400 kPa:

$$y = -0.0001x^2 + 0.0267x + 3.1635$$

Approximating polynomial equation for a series of measurements for 600 kPa:

$$y = -0.0002x^2 + 0.0509x + 3.1764$$

Approximating polynomial equation for a series of measurements for 800 kPa:

$$y = -0.0002x^2 + 0.0497x + 4.5476$$

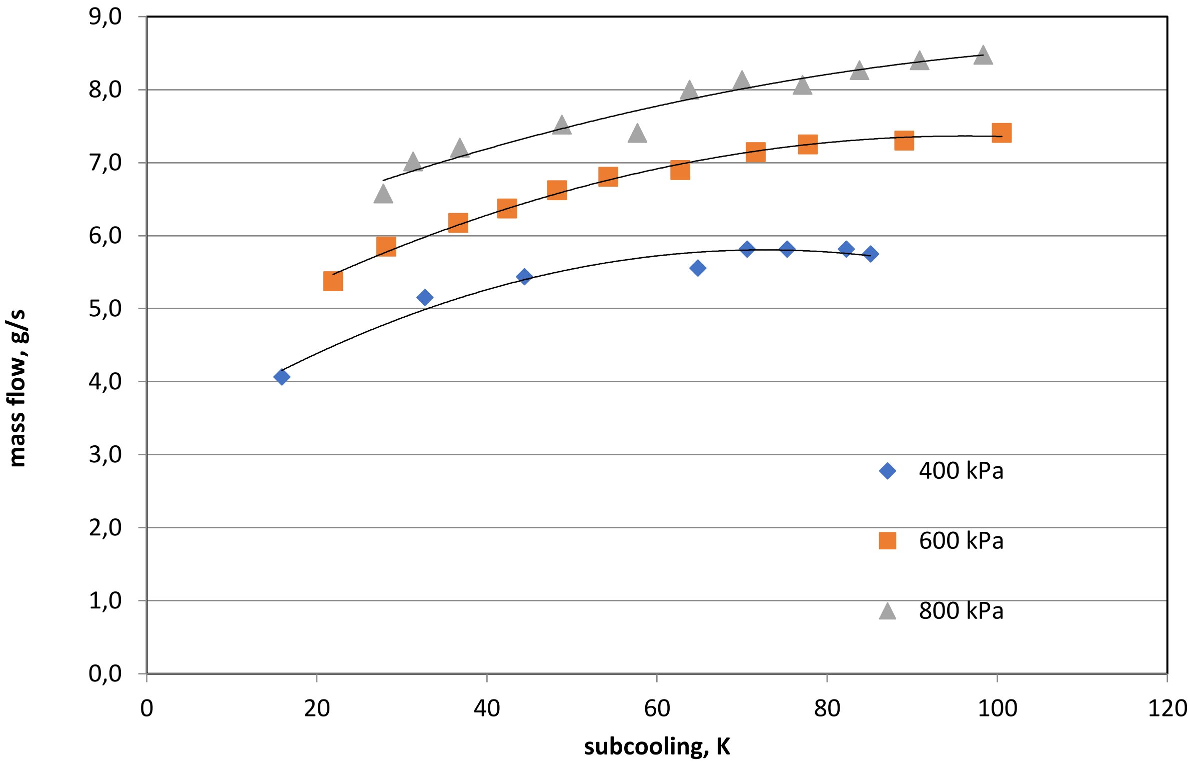

Figure 14. Approximation of operating characteristics of steam traps with nozzle diameter D=0.67mm

Approximating polynomial equation for a series of measurements for 400 kPa:

$$y = -0.0005x^2 + 0.0745x + 3.1011$$

Approximating polynomial equation for a series of measurements for 600 kPa:

$$y = -0.0003x^2 + 0.0661x + 4.1868$$

Approximating polynomial equation for a series of measurements for 800 kPa:

$$y = -0.0002x^2 + 0.0482x + 5.5631$$

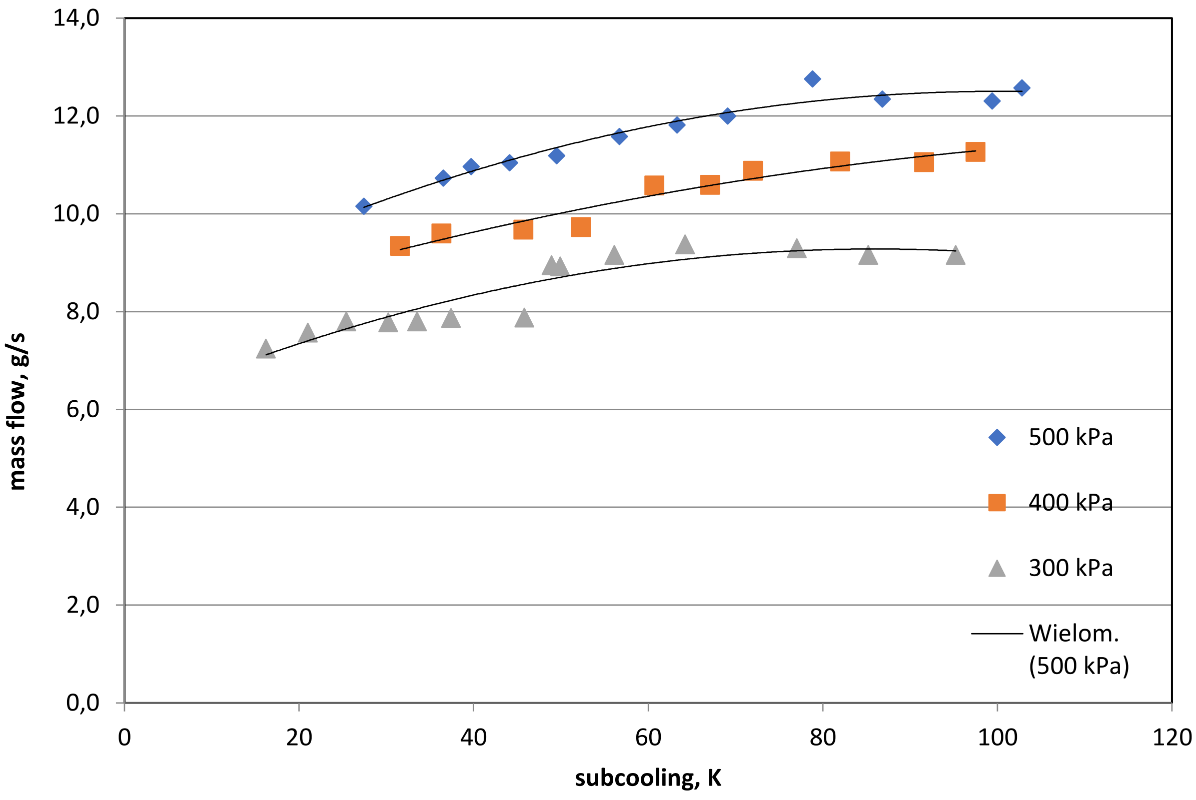

Figure 15. Approximation of operating characteristics of steam traps with nozzle diameter D=0.97mm

Approximating polynomial equation for a series of measurements for 400 kPa:

$$y = -0.0004x^2 + 0.0764x + 5.9939$$

Approximating polynomial equation for a series of measurements for 600 kPa:

$$y = -0.0002x^2 + 0.0575x + 7.6585$$

Approximating polynomial equation for a series of measurements for 800 kPa:

$$y = -0.0004x^2 + 0.0898x + 8.0063$$

4 Determination of condensate mass flux characteristics for different pressures based on functions obtained by approximation method

The mass flow characteristics of condensate from supercooling for pressures of 500 and 700 kPa were determined using the plotting method

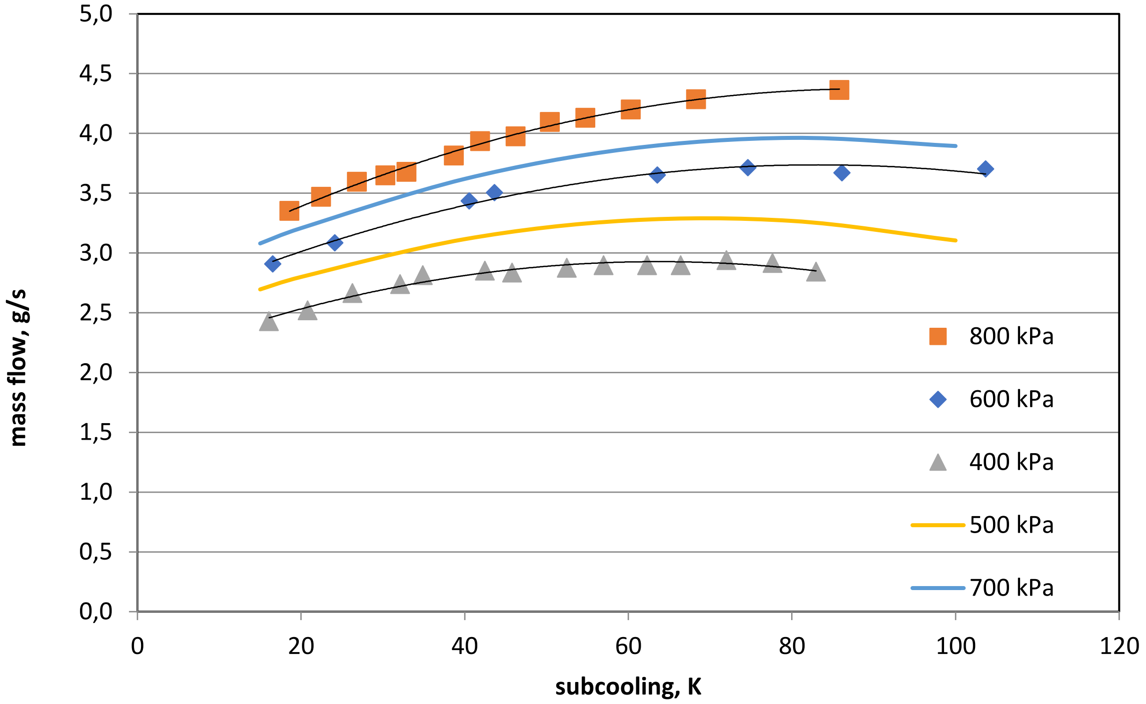

Figure 16. Determined operating characteristics of the steam trap
for pressures level equal to 500 and 700 kPa, stem trap with nozzle diameter D=0.47mm

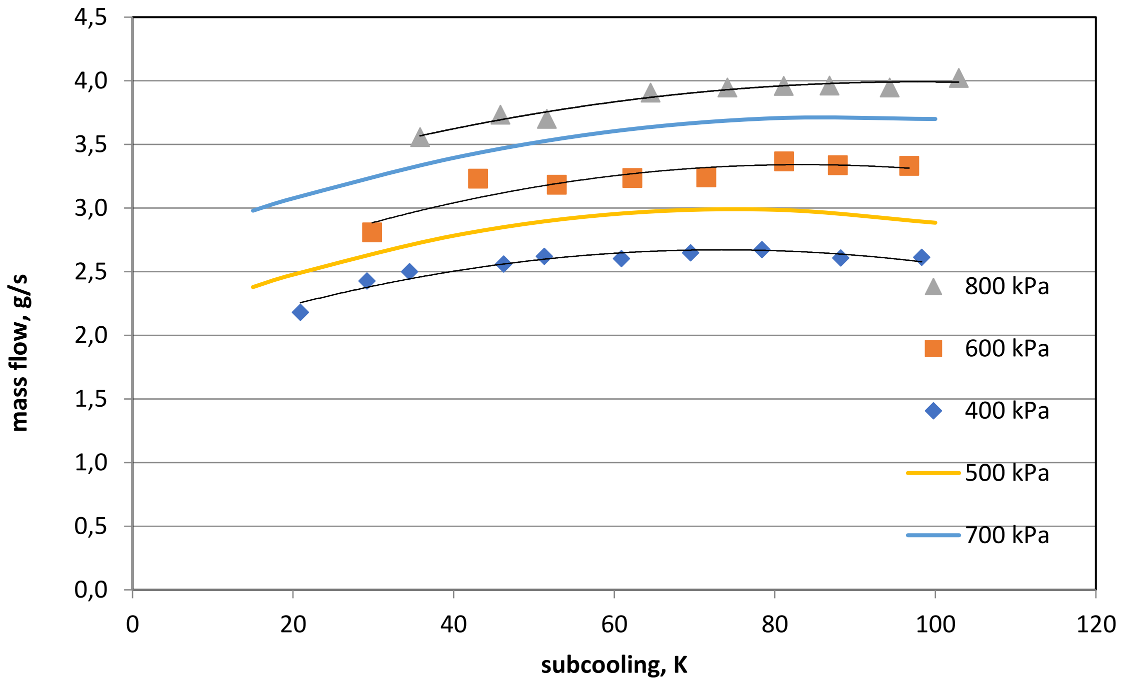

Figure 17. Determined operating characteristics of the steam trap
for pressures level equal to 500 and 700 kPa, stem trap with nozzle diameter D=0.51mm

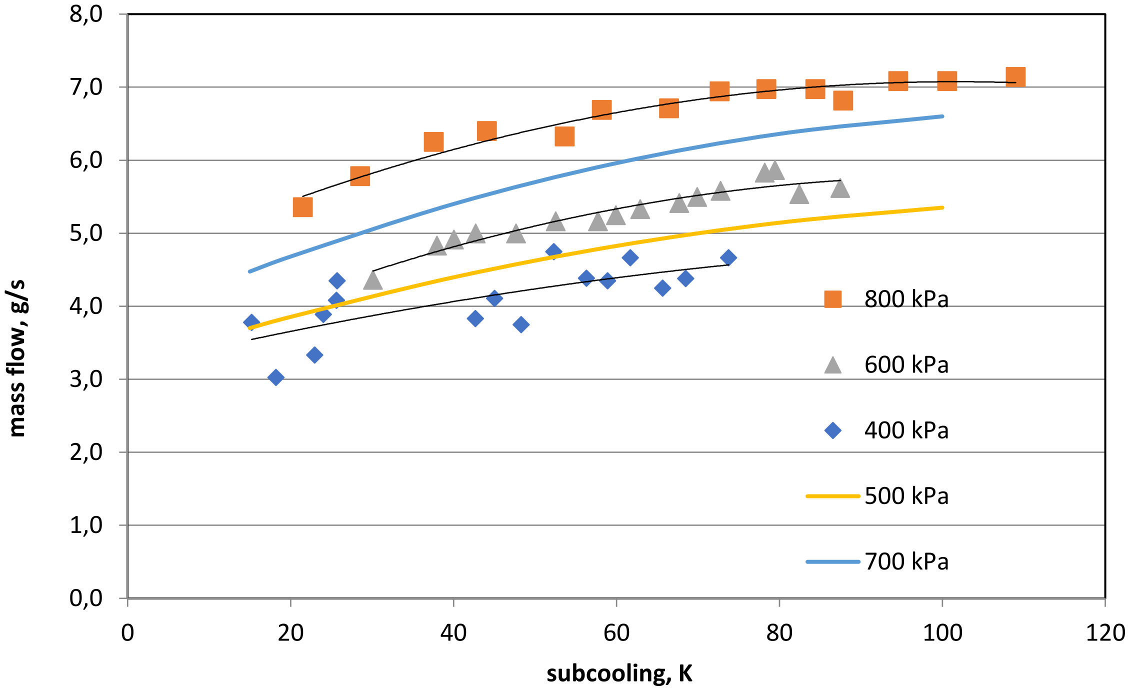

Figure 18. Determined operating characteristics of the steam trap
for pressures level equal to 500 and 700 kPa, stem trap with nozzle diameter D=0.60mm

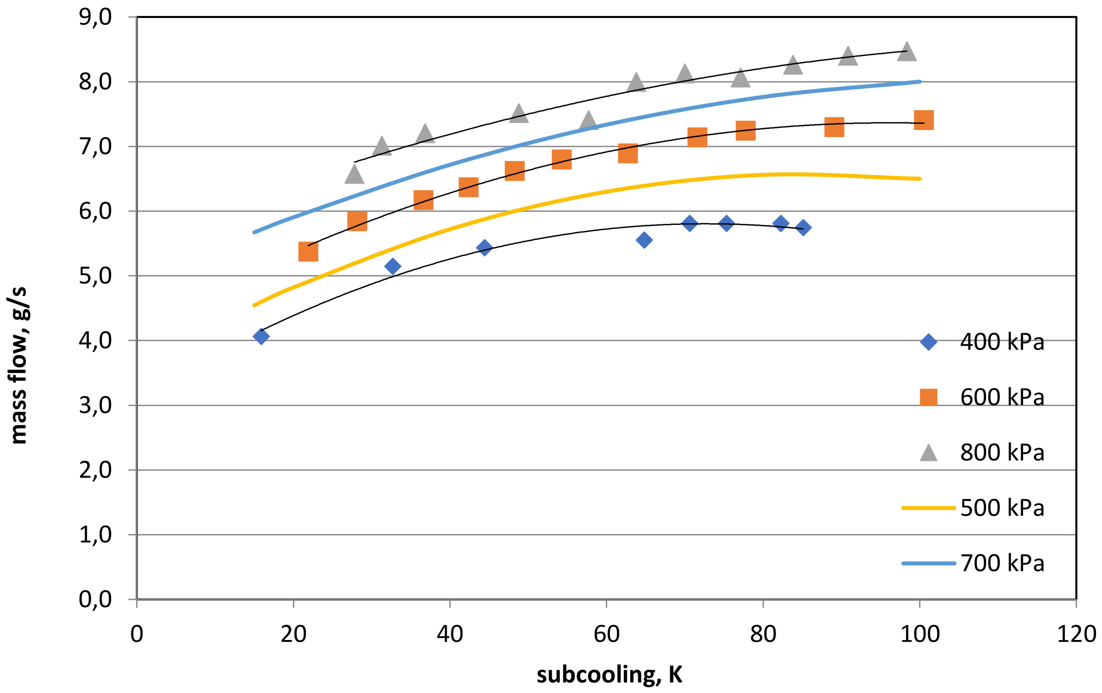

Figure 19. Determined operating characteristics of the steam trap
for pressures level equal to 500 and 700 kPa, stem trap with nozzle diameter D=0,67mm

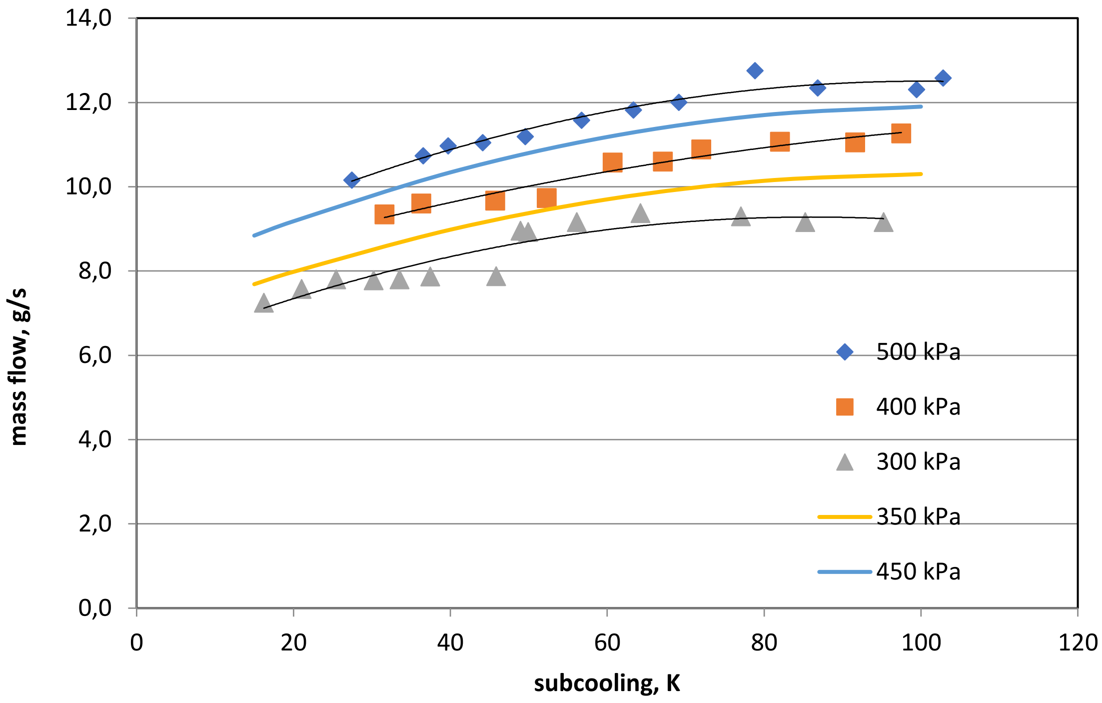

Figure 20. Determined operating characteristics of the steam trap
for pressures level equal to 350 and 450 kPa, stem trap with nozzle diameter D=0.97mm

Conclusions

The main task of this research work was to determine the operating characteristics of steam traps based on experimental research. To a large extent, this goal has been achieved. Characteristics were obtained for pressures of 4, 5, 6, 7, 8 bar and for steam traps with nozzle diameters of 0.47; 0.51; 0.60; 0.67; 0.97 mm. The supercooling of the condensate for which measurements were made ranged from 20 to 100 K. When attempts to carry out measurements for smaller supercooling values, it was not possible to obtain a steady state. There were sudden fluctuations in the temperature of the condensate and flow disturbances. In the initial phase of the research, a station equipped with a steam generator was used. It was used to simulate the conditions of the medium occurring in steam systems. Unfortunately, this generator switched on periodically. This affected periodic fluctuations in condensate pressure and made it impossible to bring it to the steady state during measurements. Plate heat exchangers were also used at this station, designed to reflect the processes carried out in real steam systems in which dehydrators are used. In this case, it turned out that these exchangers were too powerful compared to the energy given off by the condensing steam. This resulted in the inability to obtain adequate small condensate supercooling values. A decision was made to construct a new research station. The steam generator was abandoned. Instead, an electric heater was used, which was placed inside the pipes through which water flowed. In this way, instead of producing steam, water with a sufficiently high temperature was obtained, which played the role of condensate formed in steam systems. There were problems with obtaining the state established during the tests. In response to this, it was decided to use glass wool. This has brought a definite improvement. Another problem encountered was clogging of the trap nozzle opening with various particles in circulation. The solution to this problem turned out to be the use of a strainer before the dehydrator. The controller equipment proved to be very helpful in the tests, which allowed to read the results and regulate the operation of some of the devices used at the station.

Acknowledgments

This work was supported by the National Centre for Research and Development (Poland) [grant number: POIR.01.01.01-00-1259/17].

References

1. Ahlgren, R.: *What they are, what* they *do: A steam trap primer*, ASHRAE Journal 43(12) (2001) 36-39.
2. ANSI/FCI 69-1-1989: *Pressure Rating Standard for Steam Traps*, 2004.
3. ASME PTC 39: *Steam traps*, 2005.
4. Bitherm Steam Manual, 2008.
5. BN-72/8973-08, *Odwadniacze rurociągów sieci cieplnych*.
6. Einstein, D., Worrell, E., Khrushch, M.: *Steam systems in industry: Energy use and energy efficiency improvement potentials*, (No. LBNL-49081). Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2001.
7. Emerson: Manual Guides: Industrial Steam Trapping Handbook, 2017.
8. Foltynowicz I., Pyka J.: *Aproksymacja metodą najmniejszych kwadratów*, 2015
9. Fortuna Z., Macukow B., Wąsowski J.: *Metody Numeryczne*, wydanie III, wyd. WNT, Warszawa, 1993.
10. Holloway, M. D., Nwaoha, C., Onyewuenyi, O. A. (Eds.), *Process Plant Equipment, Operation, Reliability, and Control*, Wiley, 2012.
11. Hoła P.: *Zarządzanie kondensatem w procesach pary wodnej*, Pod Kontrolą 3 (2016) 10-12.
12. Jamroz, S., Mróz, K.: *Elementy ceramiczne w zaworach regulacyjnych*, Nafta-Gaz 69(4) (2013) 341-345.
13. Jinxiang W., Ning X., Zengzhi W., Qinggang W., Zhifeng W.: *Steam Trap*, 2013.
14. Łapka, P., Seredyński, M., Grzebielec, A., Szelagowski, A., Śmiechowicz, Gromadzki, E.: *Numerical investigation of the effect of the shape of the nozzle on the flash boiling, phenomenon*, in E3S Web of Conferences (Vol. 128, p. 07005). EDP Sciences, 2019.
15. Meinardus G.: *Aproksymacja funkcji i jej metody numeryczne*, Państwowe Wydawnictwo Naukowe, 1968.
16. Merritt, C.: *Process steam systems: a practical guide for operators, maintainers, and designers*, John Wiley Sons, 2015.
17. Mizielińska, K., Olszak, J.: *Parowe źródła ciepła*, Wydawnictwa NaukowoTechniczne, 2012.
18. Mobley, R. K.: *Root cause failure analysis*, Butterworth-Heinemann, 1999, ISBN: 07506-7158-0
19. Mobley, R. K.: *Maintenance fundamentals*, Butterworth-Heinemann, 2004, ISBN: 07506-7798-8
20. Northcroft, L.: *Steam trapping and air venting*, Chemical Pub, 1946.
21. Risko, J.R.: *Understanding Steam Traps*, Chemical Engineering Progress, vol. 107, no. 2, pp. 21-26, 2011.
22. Sher, E., Bar-Kohany, T., Rashkovan, A.: Flash-boiling atomization. Progress in energy and combustion science, 34(4), 417-439, 2008.
23. Szałucki K.: *Odwadniacze Gestra*, 2010.
24. Szałucki K.: *Odwadniacz w systemie parowym*, Systemy Pary i Kondensatu, 2014.
25. Szałucki K.: *W parze z parą, czli systemy pary i kondensatu prawie bez tajemnic*, Systemy Pary i Kondensatu, 2014.
26. Taplin Harry: *Steam Traps. In Boiler Plant and Distribution System Optimization Manual*, (3rd ed., pp. 1-5). Fairmont Press, 2014.
27. Tsyrulnikov, I.M. :*Methods of and means for testing steam traps*, Chem Petrol Eng 34, 494–497, 1998.