IOP Conf. Series: Journal of Physics: Conf. Series **858** (2017) 012032 doi:10.1088/1742-6596/858/1/012032

Boiling process modelling peculiarities analysis of the vacuum boiler

E N Slobodina[1], **A G Mikhailov**[1]
[1]Omsk State Technical University, 11 Mira ave., Omsk 644050, Russia

E-mail: slobodina_e@mail.ru

Abstract. The analysis of the low and medium powered boiler equipment development was carried out, boiler units possible development directions with the purpose of energy efficiency improvement were identified. Engineering studies for the vacuum boilers applying are represented. Vacuum boiler heat-exchange processes where boiling water is the working body are considered. Heat-exchange intensification method under boiling at the maximum heat-transfer coefficient is examined. As a result of the conducted calculation studies, heat-transfer coefficients variation curves depending on the pressure, calculated through the analytical and numerical methodologies were obtained. The conclusion about the possibility of numerical computing method application through RPI ANSYS CFX for the boiling process description in boiler vacuum volume was given.

1. Introduction

One can identify several areas of low and medium powered boiler technology development:

- energy efficiency improvement by heat losses reducing and maximum use of the fuel energy potential;
- boiler unit dimensions reduction by means of the fuel combustion and heat-exchange intensification in the furnace and on the heating surfaces;
- hazardous (polluting) emissions reduction;
- boiler unit operational reliability improvement.

The analysis of low and medium powered boiler equipment by domestic and foreign manufacturers showed that horizontal fire-tube boilers for vapour and hot water producing have become widely used nowadays [1-3].

The boilers of the given type require considerable steps to install chemical water treatment system of make-up water. Considerably sophisticated installations requiring expensive components for its operation are used for make-up water softening and desalting. Furthermore, when in operation, penalty payments for the discharge of salt concentrate poisoning the environment are possible [1]. The given issues can be avoided when using the vacuum hot water boiler.

The boiler operation peculiarity is that purified water is not discharged from the boiler while in operation. There is no need in boiler water regular chemical treatment, moreover, waterquality is the essential condition of boiler unit reliable and continuous operation [1].

Vacuum hot water boiler application as a heat source can solve a number of problems arising during typical boiler unit operation.

Vacuum boiler efficient operation is connected with intensive boiling and condensing processes.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

Additionally, by means of the given boiler working pressure reducing taking into account boiling temperature and as a result of maximum heat-transfer coefficients achieving at boiling and vapour condensation, significant decrease of boiler unit mass and size characteristics is possible. However, at subatmospheric pressures, heat-exchange process is known to get worse as a consequence of boiling and condensing processes intensity change. The given paper is devoted to the boiling intensification issues.

High values of heat-transfer coefficients at subatmospheric pressures are possible to achieve only by means of intensification methods application.

The article deals with the boiling process peculiarities, the possible method of boiling process intensification at subatmospheric pressures is proposed.

2. Materials and methods

Boiling is a complex process, its conditions are determined by various thermal and physical factors. Boiling intensity depends on the number of thermodynamic parameters and liquid thermal and physical properties. The parameter having the maximum impact on boiling process is pressure.

Pressure reduction and vapour bubble critical radius increase result in considerable difficulties of vapour phase formation on the heating surface that causes a significant change of boiling process internal characteristics such as growth and departure diameter rates, vapour bubbles departure frequency. Moreover, boiling transition characterized by vaporization process instability and heat-exchange non-stationarity is extended [1].

Therefore, method taking into account every change happening at the low pressure and decreasing unstable boiling risk is necessary to be used for the boiling process intensification. Finning is possible to be applied as an intensification method (Fig. 1).

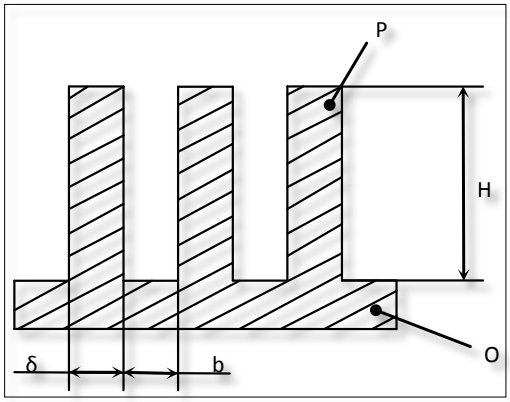


Figure 1. The finned surface computational scheme

Fin geometrical characteristics (height (H), length (l), thickness (δ) as well as adjoining fins spacing (b) should be accurately calculated to get the maximum effect, besides, the determining factor is the pressure. For instance, fins spacing should not exceed boiling liquid capillary constant value to avoid boiling crisis. The given paper concerns the research of the fin geometrical parameters to get maximum effect at the liquid boiling process intensification in the boiler vacuum volume.

3. The study of the boiling process modelling peculiarities of the vacuum boiler

The boiler heat calculation was performed by the zone method, the boiler can be conditionally divided into three zones: the furnace chamber volume (1), the convective heat exchange area (2), the vacuum volume (3) (Fig. 2).

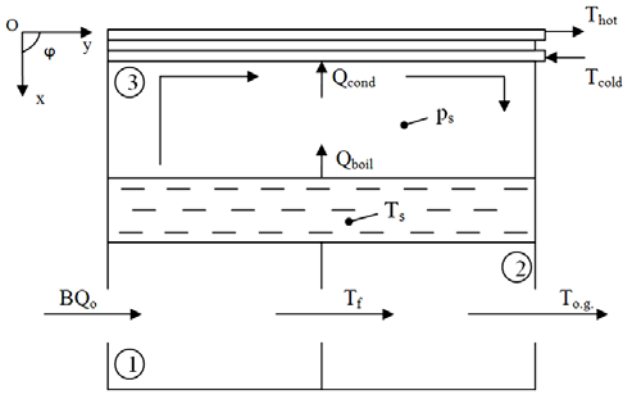


Figure 2. The calculation model of the vacuum hot-water boiler

Fig. 2 presents the following: T_T is the furnace outlet absolute temperature; $T_{o.g.}$is the outlet gas temperature; p_s, T_s are the saturation pressure and temperature; BQ_o, $Q_{boil.}$, $Q_{cond.}$ is the heat quantity generated under the fuel combustion, boiling and condensation correspondingly; T_{hot}, T_{cold} are the outlet and inlet heat carrier temperatures.

The heat exchange calculation in the hot-water boiler furnace is based on the similarity theory application to the burning processes. On the basis of this theory the heatingcalculation normative method of boiler units was developed [4].

There are different techniques for heat-transfer coefficients (a) calculation at liquid boiling. Many different parameters influence the heat transfer coefficient, such as the reduced pressure p_s, the heat flux q, the roughness and material of the heating surface and the thermophysical properties of the fluid. The heat transfer coefficient itself is defined as the quotient of the heat flux and the wall superheat:

$$a = \frac{q}{\Delta T} = \frac{q}{T_W - T_s} \tag{1}$$

Liquid heat-transfer coefficient depends only on the operating parameters (q, p), empirical dependences are applied for practical calculations [1, 5]. The calculations showed that at different techniques application the result does not change. There is a tendency of heat-transfer coefficients decreasing at pressure reducing [6]. Generally, heat-transfer coefficients decreasing demonstrates heat-exchange process intensity reducing. The given fact is unacceptable, therefore, the decision to intensify the process with the application of finning in the boiling zone was made.

Under the boiling process organization in the system of capillary slotted channels to obtain the maximum effect, the boiling liquid capillary constant variable value calculated by the presented below formula is taken into account [7]:

$$l_o = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{2}$$

where σ is the surface tension coefficient of the boiling liquid; g is the gravity acceleration; p_l, p_v are the liquid and vapour densities.

Simultaneously, the vapour bubble critical radius varying in proportion to pressure changing is taken into account. The calculation formula is given below:

$$R_{c.r.} = \frac{2\sigma T_s}{r\rho_v (T_w - T_s)} \tag{3}$$

where σ is the surface tension coefficient of the boiling liquid; p_v is the vapour density; r is the

vapourization heat; T_w is the wall temperature; *Ts* is the saturation temperature [1].

Based on the above mentioned characteristics values it is possible to conclude that the slot gap is chosen taking into consideration bubble critical radius and should not exceed boiling liquid capillary constant value [1, 7].

Regarding the fin height, the optimal value is possible to be chosen taking into account fin effectiveness, the calculation formula is presented below:

$$E = th\left(\frac{H}{\delta}\right)\sqrt{2Bi} \Big/ \frac{H}{\delta}\sqrt{2Bi} \tag{4}$$

In paper [7] the calculation equation for heat-transfer coefficient determining at liquid boiling on the finned surface in capillary channels under two-dimensional position is represented. The equation under discussion makes possible to evaluate the obtained effect of finning.

However, analytical solution of the heat distribution problem in the fin and liquid volume under multidimensional position is connected with considerable difficulties. It is not always possible to take into account fin end surface heat-exchange.

For the most reliable results obtaining, two methods (analytical and numerical) combination is necessary to be applied.

Different subcooled nucleate boiling models based on local parameters (temperature, void fraction or for example turbulence intensity) could be used without any difficulty in CFD. One of them was presented by Kurul and Podowki and it is the model applied in this solver [8].

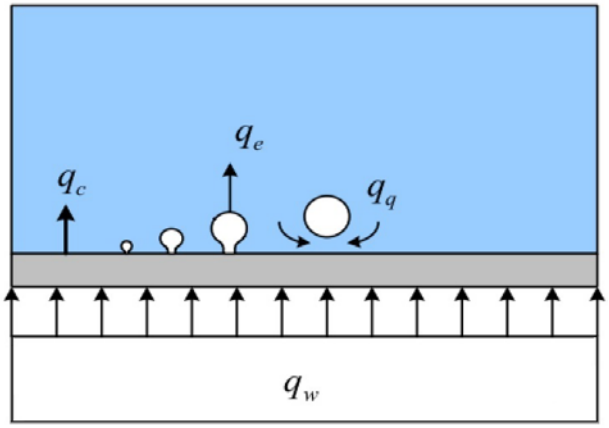


Figure 3. Heat flux partitioning according

The basic idea in the model is that the heat transfer originates from three different mechanisms between the heated wall and the liquid phase:

$$q_w = q_c + q_e + q_q \tag{5}$$

whereq_c, q_e and q_q denote respectively single-phase convective heat flux density, evaporation heat flux density and quenching heat flux density (Fig. 3).

At the heated wall, bubbles are formed at the nucleation sites due to evaporation of liquid at the wall and one therefore assumes that part of the wall heat ux density is directly used to transform the liquid into vapor. Bubbles grow and reach a critical size at which they detach from the wall. Once a bubble leaves the wall, the volume previously occupied by it is filled with cooler liquid, which will receive heat from the wall. The heat transfer to this cooler liquid is called quenching. The ratio of the wall influenced by quenching Aq is thus closely depending on the evaporation and the bubble lift-off size. Finally, the rest of the wall 1 – Aq is governed by single-phase convection.

Boiling model RPI is possible to be used as a numerical method. In the given model, boiling

process followed by convection is considered in the channels system.

The presented mathematical models contains 8 independent equations:

- 2 mass conservation equations for the liquid and gas phases;
- 2 momentum conservation equations for the liquid and gas phases;
- 1 energy conservation equation for the liquid phase;
- 1 interfacial area concentration transport equation;
- 2 additional partial derivative equations for the turbulence of the liquid phase.

Using various closures laws, all the parameters appearing in these equations have been expressed as a function of 8 independent variables:

- the void fraction;
- the gas velocity;
- the liquid velocity;
- the specific enthalpy of the liquid phase;
- the interfacial are concentration;
- the turbulent kinetic energy of the liquid phase;
- the turbulent dissipation rate of the liquid phase;
- the pressure.

Furthermore, the initial and boundary conditions are defined [9].

As a result of the conducted calculation studies, heat-transfer coefficients variation curves calculated by using analytical and numerical methods depending on pressure were obtained.

Calculation and empirical data comparison curves by the following authors: V.P. Isachenko, V.A. Osipov, A.S. Sukomel, Ju.M. Lipov, Ju.M. Tretjakov [6], using correlation equations, are represented in Fig. 4. The comparison was carried out with calculations under similar conditions obtained in ASYSCFX software. Calculation ratio a_r/a_s, where $a_r$is heat-transfer coefficient on the finned surface, a_s is heat-transfer coefficient on the smooth surface, the variable is pressure in vacuum volume, is represented in Fig. 5. Calculations were conducted taking into account subatmospheric pressures.

Having fixed pressure to the heat-transfer coefficient maximum value (60 kPa), the fin geometry impact analysis was conducted. At the fixed height value, fin length changed, variation range amounted from 0.05 to 0.1 m, and slot gap value varied from 0.001 to 0.01 m. Obtained computational data made possible to choose geometrical characteristics with maximum effect of finning.

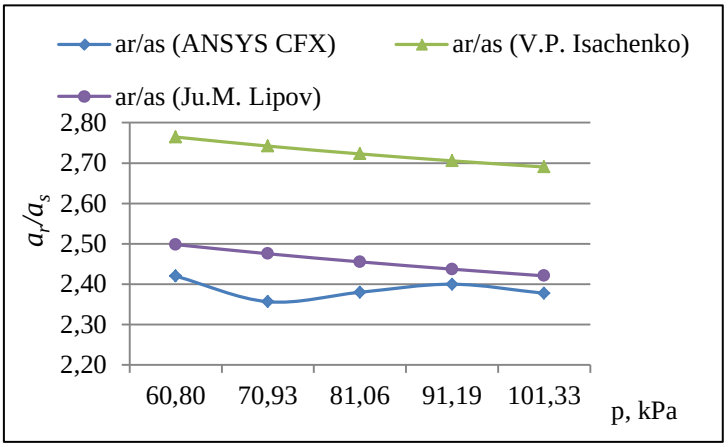


Figure 4. The comparison of relative heat-transfer coefficients calculation results at boiling according to different approaches

Reduced heat-transfer coefficient dependence on the finned surface geometrical characteristics is represented in Fig. 5.

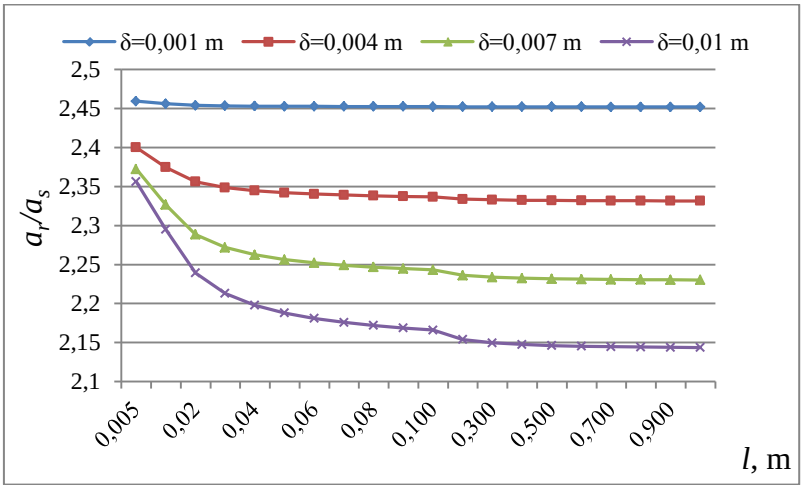


Figure 5. Reduced heat-transfer coefficient dependence on the finned surface geometrical characteristics

Heat-transfer coefficients values mean difference (Fig. 4) obtained at heat-exchange process calculated modelling, under boiling, varies from 2 to 12 % at the pre-determined pressure from 60 to 101 kPa.

Maximum difference between numerical and analytical values calculated according to Ju.M. Lipov, Ju.M. Tretjakov are minimal at specified initial and boundary conditions as a result of uneven temperature distribution impact on the heated surface and convective phenomena.

According to the computational data, it may be concluded that fin length (*l*) shortening (Fig. 5) results in heat-exchange specific influence increasing on the side surface provided that fin end surface area value tends to the minimal values. Thus, one could affirm that rectangular-cutout tenons fins appliance taking into account slot gap not exceeding capillary constant is the most effective option of finning for liquid boiling process intensification. Under the given conditions, reduced heat-transfer coefficient increases.

4. Conclusion

The studies have shown that at heat-exchange process modelling according to the boiling approach, RPI compared with analytical approaches ranges from 2 to 12 % under predetermined pressure from 60 to 101 kPa. There are minimal differences when comparing with Ju.M. Lipov, Ju.M. Tretjakov approach at specified initial and boundary conditions by taking into account subatmospheric pressures. Therefore, model RPI ANSYS CFX calculation numerical method is possible to be used for boiling process describing in the boiler vacuum volume.

The calculation showed that the most effective finning option for the liquid boiling process intensification is the rectangular-cutout tenons fins appliance taking into account the slot gap not exceeding capillary constant. The given technical solution resulting in reduced boiler unit dimensions is possible for applying in the boiler vacuum volume to intensify boiling process.

Research made in the framework of the research work №17087B Omsk State Technical University.

References

[1] Slobodina E N 2016 Oil and Gas Engineering *The peculiarities of the boiling process at subatmospheric pressure* pp 395–399
[2] Annaratone D 2008 *Steam generators* (Springer-Verlag Berlin Heidelberg) p 434
[3] Mikhailov A G, Batrakov P A, Terebilov S V, E. N. Slobodina 2014 Dynamics of Systems, Mechanisms and Machines *Gas-tube boilers: issues of classification and thermal calculation* pp 1–4
[4] Slobodina E N, Mikhailov A G 2016 Oil and Gas Engineering *The analysis of the condensation process impact on the vacuum boiler operating efficiency* pp 395–399

[5] Feldmann H and Luke A 2008 International Refrigeration and Air Conditioning Conference at Purdue *Nucleate boiling in water for different pressures* pp 1–8
[6] Slobodina E N 2015 Omskij nauchnyj vestnik *Vlijanie processa kipenija v razrjazhennoj polosti na jeffektivnost' raboty vakuumnogo kotla* (Ser. Pribory, mashiny i tehnologi №3 (143)) pp 185–187
[7] Korneev S D 2006 Izvestija MGIU 1 (2) *Vlijanie teplofizicheskih svojstv materiala orebrennoj poverhnosti na vybor ee optimalnyh geometricheskih harakteristik* pp 56–61
[8] Kurul N and Podowski M Z 1991 Proceedings of the 27th National Heat Transfer Conference *On the modeling of multidimensional effects in boiling channels* pp 21–26
[9] Inc. ANSYS. ANSYSCFX-Solver Theory Guide, 12.1 edn.(November 2009) p 372