International Conference on Oil and Gas Engineering, OGE-2016

The analysis of the condensation process impact on the vacuum boiler operating efficiency

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Abstract

The paper represents the research results of the condensation process impact in vacuum volume on the vacuum boiler operating efficiency. The calculation method of the vacuum hot-water boiler taking into consideration heat transfer under condensation is proposed. The studying of the condensation process in vacuum volume makes possible to identify the disadvantages influencing over the vacuum boiler efficient operation. The selection of heat exchange intensification rational methods on the basis of the obtained information makes possible to use the vacuum boiler as a heat source for autonomous heat supply systems in industry.

Keywords: condensation; pressure; heat transfer; efficiency

1. Introduction

To improve the applying and achieve economically feasible efficiency of energy resources usage is possible due to the development and implementation of new technologies and equipment. The vacuum hot-water boiler not requiring high financial expenses at operation, having simple construction and being safe in use can be offered for the autonomous heat supply systems.

The boiling and condensation processes taking place in vacuum volume of the given boiler have a considerable impact on the vacuum boiler operating efficiency. The heat exchange capacity reduction in vacuum volume resulting from the pressure lowering decreases the device efficiency. The boiling and condensation processes at subatmospheric pressure differ from the processes taking place at atmospheric pressure, therefore, it is necessary to examine the peculiarities of each process to select optimal methods of intensification.

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For a long period of time, no due attention was paid to the condensation processes under the heat and mass transfer equipment operation, the process was supposed not to require the appliance of extended heating surfaces and other intensification methods. In the vacuum boiler condensation is an important process influencing the boiler operating efficiency and it requires more detailed study of the given process peculiarities at subatmospheric pressure. The research of this process characteristics makes possible to define the spectrum of problems and select the heat exchange intensification rational methods. The vacuum hot-water boiler energy efficiency improvement by means of heat and mass transfer intensification in vacuum volume makes possible to construct the medium powered high efficiency industrial sample for the autonomous heat supply system.

The present paper deals with the condensation processes in boiler vacuum volume taking into account the boiling process.

2. The study subject (Model, Process, Device, Synthesis, Experimental procedure, etc.). Condensation process modelling in vacuum volume

The condensation represents the process of vapor (gas) conversion to the liquid or solid state. The heat release at the phase transformation inextricably connects the vapor condensation process with the heat exchange. Condensation can occur in the vapor volume or on the cooled heat exchange surface.

In vacuum boilers, the question is about the saturated vapor condensation to the liquid state on the cooled heat exchange surface, providing that the surface temperature is lower than the saturated one at the defined pressure.

The saturated vapors are often condensed on the horizontal tubes external area in vacuum boilers, to define the heat transfer coefficient value is possible according to the formula [1]:

\[ \alpha = 0.798 \sqrt[4]{\frac{\lambda_l \rho_l^3 \varphi}{\mu t_s (t_s - t_w) d}} \]  

where \( \lambda_l \) is the heat conductivity of the liquid phase; \( \rho \) is the density of the liquid phase; \( g \) is the gravity acceleration; \( \mu \) is the dynamic viscosity; \( t_s \) is the saturation temperature; \( t_w \) is the wall temperature; \( d \) is the typical dimension.

There is also a possibility of condensation on the inclined and vertical surfaces.

In case of condensation on the vertical surface, the heat transfer coefficient is calculated using the following formula [1]:

\[ \alpha = 0.943 \sqrt[4]{\frac{\lambda_l \rho_l^3 \varphi^2}{\mu t_s (t_s - t_w) h}} \]  

where \( \lambda_l \) is the heat conductivity of the liquid phase; \( \rho \) is the density of the liquid phase; \( g \) is the gravity acceleration; \( \mu \) is the dynamic viscosity; \( t_s \) is the saturation temperature; \( t_w \) is the wall temperature; \( h \) is the wall height.

In case of the inclined surface, the gravity acceleration vector projection on an axis \( Ox \) is necessary to introduce into the basic equation of motion [1]:

\[ g_x = g \cos \varphi \]  

where \( \varphi \) is the angle formed by the gravity force direction and coordinate axis \( Ox \); the axis \( Ox \) is oriented in the film direction [1].

Consequently, the following formula is obtained for the inclined surfaces [1]:
To ensure the boiler operation at the maximum possible efficiency, the following equation should be performed [2]:

\[
\frac{q_{\text{boil.}}}{q_{\text{cond.}}} = \frac{F_{\text{cond.}}}{F_{\text{boil.}}}
\]  

(5)

where \(q_{\text{boil.}}\) is the heat flow at boiling; \(q_{\text{cond.}}\) is the heat flow at condensation; \(F_{\text{boil.}}\) is the heat exchange surface area at boiling; \(F_{\text{cond.}}\) is the heat exchange surface area at condensation.

The given equation is determined by the boiling and condensation processes relation.

3. Methods

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), and the vacuum volume (3) (Fig. 1).

Figure 1 presents the following: \(T_f\) is the furnace outlet absolute temperature; \(T_{o.g.}\) is the outlet gas temperature; \(p_s, T_s\) are the saturation pressure and temperature; \(\dot{Q}_{boil.}, \dot{Q}_{cond.}\) is the heat quantity generated under the fuel combustion, boiling and condensation correspondingly; \(T_{\text{hot}}, T_{\text{cold}}\) 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 heating calculation normative method of boiler units was developed [3, 4].

The heat exchange in the furnace is defined according to the formula connecting the furnace outlet combustion products dimensionless temperature (\(\theta_f\)) with the Bolzmann criterion (Bo), the Buger criterion (Bu), the furnace emissivity factor (\(a_i\)) and the parameter (M), taking into account the temperature distribution along the furnace height:

\[
\theta_f = \frac{T_f}{T_a} = \frac{Bo^{0.6}}{M \cdot Bu^{0.3} + Bo^{0.6}}
\]  

(6)

The furnace outlet combustion products dimensionless temperature (\(\theta_f\)) represents the ratio of the furnace outlet actual absolute temperature (\(T_{\text{act.}}\)) to the theoretical absolute temperature of the combustion products (\(T_a\)).
The heat transfer in vacuum volume is defined by the balance method taking into consideration heat transfer coefficient at boiling and condensation for the horizontal surface. The effectiveness criterion is the vacuum boiler gross efficiency.

4. Results and discussion

Condensation is the essential process impacting the vacuum boiler operating efficiency. The heat transfer coefficient highest value is possible to obtain under the drop condensation that is difficult to maintain. Condensation can occur in vapor volume or on the cooled heat exchange surface. In vacuum boilers the question is about the saturated vapor condensation to the liquid state on the cooled heat exchange surface, provided that the surface temperature is lower than the saturation temperature at the defined pressure [5,6]. Heat release under the phase transformation inextricably connects the vapor condensation process with heat exchange. The heat transfer coefficient at condensation, first of all, depends on the saturation vapor temperature (pressure), while its variation is determined by the temperature difference and geometrical characteristics of the heat exchange surface (Fig. 2).

![Fig. 2. The surface geometrical parameters impact on the heat transfer coefficient under condensation.](image)

The heat transfer coefficients decrease with $h(d)$ increase, and, on the contrary, the film thickness grows. The decrease of heat transfer coefficients is explained by the film thickness increase, since the thermal resistance increases simultaneously.

![Fig. 3. The heat transfer coefficient dependence on the angle φ under condensation for the curved surface.](image)
Fig. 3 shows the heat transfer coefficients ratio dependence (\(\alpha_1\) is the curved surface heat transfer coefficient; \(\alpha_2\) is the heat transfer coefficient on the vertical surface) on the angle (\(\phi\)) for the curved surface. The maximum value of the heat transfer relation coefficient corresponds to the vertical wall (the angle is \(\phi = 0\)) while the minimum value does to the horizontal one (the angle is \(\phi = 90\)). Condensation process is carried out on the vertical wall more efficiently than on the horizontal one as the gravity force acting along the condensate motion on the surface stimulates film thickness decreasing.

The condensation process intensification is possible by means of the heating area increase including by means of finning. In vacuum boilers boiling and condensation processes are inextricably connected. To obtain maximum effect, the intensification methods are necessary to be choosen, taking into account the specific heat flows and heating area ratios equality (5).

The fulfillment of this condition makes possible to intensify the heat exchange process in vacuum volume and to obtain the maximum possible boiler efficiency (Fig. 4).

![Fig. 4. The boiler efficiency dependence on the pressure taking into account geometrical characteristics.](image)

5. Conclusion

The condensation process peculiarities were considered in the present paper. The direct relation of the condensation and boiling processes was specified. The heat transfer coefficient relation under condensation to the heat carrier thermal and physical properties (temperature, pressure) and geometrical characteristics of the heat exchange surface was confirmed. The condensation process is the most intensive on the vertical surface in comparison with the horizontal one. The maximum effect is achieved at the pressure of 60 kPa and at the areas ratio \(F_{\text{cond.}}/F_{\text{boil.}}\) is equal to 1.13, the vacuum boiler efficiency increasing amounts to 2 %. The range of pressure and areas ratios does not exceed the outlet gas temperature acceptable limit from 120 to 170°C. The obtained results create prerequisites for the vacuum fire-tube boiler using as an industrial sample for the autonomous heat supply systems.

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