Turbulent flow investigation of the vacuum boiler at boiling

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Abstract. Viscosity coefficient defining methods taking into account the turbulent component under the boiler various operating conditions at the subatmospheric pressure are considered in the paper. Currently, addressing this problem is of particular relevance for the vacuum boilers heat-exchange problems solution. The viscosity coefficient dependences in a wide range of the specific heat fluxes at the free convection and bubble boiling are obtained. The study results were obtained by means of the software complex ANSYS CFX and RPI model.

Key-words: turbulence, viscosity, boiling process, boiler

1. Introduction
At present, there is an upward trend of heat and electric energy production growth in the world. Hence, the consumption of the fossil fuel, which resources are exhaustible, increases. The emerging problem becomes one of the fundamental ones in the modern society. In the fuel resource-limited settings, there is a need to develop cost-effective and resource-saving technologies. The alternative energy sources development contributes to solving the problem, but unfortunately, there is no opportunity to meet the world’s energy requirements and abandon the traditional fuels. Therefore, the need to develop resource-saving technologies for reducing the traditional fuels use remains. In the heat and power industry, the question is primarily the heat sources, namely the boilers. One of the promising alternatives is the vacuum boiler. The vacuum boilers operation main feature is boiling at the subatmospheric pressure.

2. Problem statement
Most of the flows being the issue of practical concern when calculating and designing the boilers are turbulent ones. They are unsteady by their nature. And in some cases they are complicated by the additional excitation, for example, bubble boiling. Such phenomena occur in the fire-tube boilers, most frequently in vacuum boilers at the reduced pressure when boiling and condensation processes are inextricably linked. The boiling process is a complex phenomenon to be divided into several modes depending on the local flow conditions. Thermal conductivity, density, specific heat capacity, thermal diffusivity and viscosity coefficients have the greatest influence on the heat exchange at boiling and convection. The given variables have the definite values for each substance and are determined by such parameters as pressure and temperature. The convective heat and mass exchange differential equations include the thermal physics variables values comprising the viscosity one. The equations solving result is defining the heat transfer coefficient. Thus, the viscosity coefficient correct determination is important in defining the boiler efficiency.
When studying the turbulent flow as a fluid flow possessing the effective viscosity, thermal conductivity and diffusion coefficient changing in space, the effective transport properties calculation problem for the boilers thermal calculation of boilers should be solved.

3. Theory
The liquid phase effective viscosity is the molecular and eddy viscosity sum:

$$\mu_l^{\text{eff}} = \mu_l + \mu_l^t$$

There are various methods of the liquid phase eddy viscosity calculating. A model with empirical transport coefficients in the turbulent flows equations is one of such methods. The most known calculation of the effective viscosity for the turbulent motion was proposed by Prandtl [1, 2, 3]. The eddy viscosity calculation is based on the so-called mixing length hypothesis and makes it possible to define $\mu_t$ by the following equation:

$$y = U_l \frac{\partial}{\partial y}$$

Where $l$ is the mixing length; $\rho$ is the liquid density; $U$ is the flow velocity; $y$ is the distance along the normal to the flow motion. The given equation changes the $\mu_t$ defining problem to the $l$ calculating one. However, the Prandtl hypothesis advantage is that $l$ varies in space within more narrow limits than $\mu_t$. In free turbulent flows, $l$ is usually equal to $l/10$ of the area width where the tangential stresses have the significant values. In the boundary layer adjacent to the wall, the mixing length very close to the wall is $\sim 0.4y$, and in the boundary layer outer part it is about 0.1 of this layer thickness. Taking into consideration some assumptions, $l$ defining makes it possible to calculate the multidimensional turbulent boundary layers variables accurately. S. V. Patankar and D. B. Spalding [1, 2, 3] used the above described statements having included the parabolic differential equations to the general solving procedure. For calculating the effective viscosity, it is possible to use other dependences. L. Prandtl [2] justified the free turbulent flows to be calculated with the acceptable accuracy by assuming that the coefficient $\mu_t$ is constant through the boundary layer thickness and is defined according to the formula:

$$\mu_t = c \delta \rho \left(U_{\text{max}} - U_{\text{min}}\right)$$

where $\delta$ is the boundary layer thickness; $U_{\text{max}}$ and $U_{\text{min}}$ are the maximum and minimum velocities of the boundary layer section; $c$ is the constant of order 0.01.

The liquid density $\rho$, in the case of the flow cross section change should be averaged. Equation (1) is used much less frequently than equation (2), and it is preferable to the former only in one respect, namely it does not result in the contradictory requirement of $\mu_t$ vanishing at the boundary layer point, where $\frac{\partial U}{\partial y} = 0$.

Nevertheless, the dependences can be used only with certain restrictions in cases of the reverse flows having no dominant flow direction. Kolmogorov [2] - Prandtl [6] hypothesis, according to which the eddy viscosity coefficient $\mu_t$ is related to the pulsation motion kinetic energy $k$ by the following ratio, is more acceptable for the mentioned problems:

$$\mu_t = c \delta \kappa^{0.5} l$$

where $l$ is the turbulence scale.

The particular advantage of equation (3) and turbulent flow corresponding model are the possibility of deriving the differential equation in which the kinetic energy $k$ plays the role of the main dependent variable. Moreover, D. K. Rotta [2] proposed the equation of the turbulence scale defining $l$. These equations are elliptic. For them it is necessary to determine the constants empirically, some of the constants are included into equation (1), while others appear in the equations describing the turbulent
flow dissipation and diffusion. Empirical characteristics of the effective thermal conductivity and mixture components diffusion coefficients values are also required.

The turbulence models with two equations are widely used, as it is a good compromise between the calculations accuracy and numerical solution costs. The given models are more complicated than examined above. The characteristic length and velocity values are defined by using different motion equations.

These turbulence models are called $k$-$\varepsilon$ and $k$-$\omega$ ($\varepsilon$ is dissipation, $\omega$ is turbulent frequency) or the model with two equations. For defining the Reynolds stresses dependence on the velocity and eddy viscosity gradients values, the diffusion gradient hypothesis is used. The eddy viscosity is modeled as a function of the turbulent velocity and turbulent characteristic length. The turbulent velocity is calculated by means of the turbulent kinetic energy equation obtained by solving the motion equation. The turbulence characteristic length is determined by two characteristics of the turbulent region, namely the turbulent kinetic energy $k$ and dissipation $\varepsilon$. The turbulent kinetic energy dissipation value is defined by the motion equation solving.

In the model, the eddy viscosity is assumed to be related to $k$ and $\varepsilon$ by the formula:

$$\mu_t = C_\mu \rho \frac{k^2}{\varepsilon}$$

where $\mu_t$ is the turbulent dynamic viscosity, $C_\mu$ is the reference constant [7].

The model $k$-$\omega$ contains the equations of continuity, moments, kinetic energy, turbulent frequency, and assumes that the eddy viscosity is related to the turbulence frequency $\omega$ by the following ratio:

$$\mu_t = \rho \frac{k}{\omega}$$

A characteristic feature of $k$-$\omega$ model is the boundary layer processes description at the low $Re$ numbers.

The discussed above mathematical models are possible to be used for describing the combustion processes in the turbulent motion of the fuel-air mixture and water volume convective heat exchange processes. In the paper, $k$-$\varepsilon$ model complemented by the state, through flow equations and corresponding initial and boundary conditions is preferred [7], taking into account the interaction of fuel and oxidizer elements during the combustion process.

Turbulence at the liquid phase boiling is complemented by the equation describing the bubbles influence on the turbulence theory developed by Y. Sato [8]:

$$\mu_{t, b} = \frac{1}{2} C_{\mu, b} D_s a \left\| \frac{U_i}{U} - \hat{U} \right\|$$

Thus, the liquid phase eddy viscosity equation is as follows:

$$\mu_{t, b} = C_\mu \rho \frac{k^2}{\varepsilon} + \frac{1}{2} C_{\mu, b} D_s a \left\| \frac{U_i}{U} - \hat{U} \right\|$$

where $a$ is the mass phase fraction, $D_s$ is the bubble diameter, $C_\mu$ is the reference constant.

The gas phase turbulence impacts the liquid phase and is taken into account by introducing the additional coefficient defined as the ratio of the dispersed phase velocity fluctuations root mean square value to the continuous phase, as well as the dependence on the local parameters such as the steam content and considers the liquid turbulence effect on the steam medium.

This method described by H. Rusche [9] means that the additional differential equations are not required. The gas phase effective viscosity is expressed as the equation:

$$\mu_{g, eff} = \mu_g + C_\mu \mu_t$$
Heat and mass transfer process calculation taking into consideration the effective viscosity was performed by using $k-$\(\varepsilon\) model of ANSYS CFX, while boiling the RPI model of ANSYS CFX was used [7, 10].

4. Experimental results
The working substances and their physical properties are chosen by using the CFX operating components library [7]. The numerical calculation was performed in the software system ANSYS CFX by using the RPI model describing the boiling process. Moreover, the initial and boundary conditions were set taking into account the vacuum boiler thermal calculation.

![Figure 1. The ANSYS CFX boiling process modelling results.](image1)

The velocities and temperatures distribution in the volume at the pressure of 60.80 kPa is represented in figure 1. It is evident that thermal fluctuations are accompanied by the convective phenomena at nucleate boiling. Besides, the maximal temperatures range corresponds to the fire tube wall and liquid interface region. The volume temperature remains unchanged and equals to the saturation temperature, and velocities reach the maximum values due to the liquid volume turbulent phenomena.

![Figure 2. Eddy viscosity dependence on the heat flux density.](image2)

Based on the calculation results, the graphical dependence illustrating the eddy viscosity and heat flux density relation for the boiling liquid – curve 1 and for the non-boiling liquid – curve 2 is presented in figure 2. Saturation temperature is 86 °C, operating pressure is 60.80 kPa.
Figure 3. Heat transfer coefficient dependence on the heat flux density.

The graphical dependence demonstrating the heat flux density impact on the heat transfer coefficient at liquid boiling is shown in figure 3. With increase of the heat flux, the heat transfer coefficient grows with a simultaneous viscosity increase at the liquid nucleate boiling.

5. Results discussion
The liquid fluid viscosity is slightly depends on the pressure and is a temperature function. Turbulent excitations caused by the heat flux density increase from 10.000 to 30.000 W/m² and presented in figure 1 result in the eddy viscosity increase by 20 %. The transition to the nucleate boiling mode determines the eddy viscosity growing by 29 %.

6. Conclusions
The total viscosity change can reach 49 %. This impacts the liquid flow and heat exchange of the wall, while the heat transfer coefficient increases by 2.15 times. The boiling process intensification has a significant impact on the boiler efficiency as a whole.

7. References
[1] Pashkov L T 2002 The Foundations of the Combustion Theory (Moscow: MEI)
[2] Gosmen A D, Pan V M and Ranchel A K 1972 Numerical Methods of Studying the Viscous Fluid Flows (Moscow: Mir)
[3] AlekseevBV 1985 Physical Gas Dynamics of Reacting Media (Moscow: Vyssh. Shk.)
[4] Patankar S V, Kalabin E V and Yankov G G 2003 Numerical Solution of the Thermal Conductivity and Convective Heat Transfer Problems during Channels Flow (Moscow: MEI)
[5] Spalding D B and Taborek J 1983 Heat Exchanger Design Handbook (Washington: Hemisphere Pub. Corp)
[6] Prandtl L 1942Z. angew. Math.und Mech. 22(5) 241–43
[7] ANSYS CFX-Solver Theory Guide 2006 ANSYS CFX Release 11.0 (Canonsburg: USA)
[8] Sato Y et al. 1981 Int. J. Multiphase Flow7 167–78
[9] Rusche H 2002 Computational Fluid Dynamics of Dispersed Two-Phase Flows at High Phase Fractions. Ph.D. thesis (London, Imperial College)
[10] Končar B, Krepper E and Egorov Y 2005 CFD Modeling of subcooled flow boiling for nuclear engineering applications Proc. Int. Conf. Nuclear Energy for New Europe ed J Potocnik (Bled, Slovenia) pp 140-54