Selection of optimum inclination angle of a nozzle at circulatory heating of fuel oil in the RVS-3000 tank

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Abstract. The paper presents the mathematical model and the numerical studies results of heat transfer and hydrodynamics at circulatory heating of the M100 fuel oil in the RVS-3000 tank. Calculations for various inclination angles of the nozzle in the range of 40° to -40° in increments of 10° were made. The winter storage period of fuel oil in the fuel tank is considered. Comparison of the tank heating time up to the hot storage temperature (60°C) and up to the fuel temperature before feeding to the nozzles for combustion (90°C) is performed.

Introduction

Most of the research on heat transfer and hydrodynamics at circulatory heating of the fuel oil was carried out by the staff members of the Research center for energy problems Kazan Scientific Center of Russian Academy of Sciences under the guidance of the corresponding member of the RAS Yu.G. Nazmeev [1 – 5]. The most significant results for storage of liquid organic fuel and oil products in tanks and tank fields equipped with circulatory heating systems are presented in the book [1]. This work also describes mathematical models and the numerical studies results of thermal and hydrodynamic processes for submerged plane straitened, and free jets of viscous liquid in the filled storage tanks.

In [6] heat exchange processes in the fuel oil storage tank in the presence of a heat source at the lower boundary were simulated, taking into account interaction with the environment. A comparative analysis of the dependences of mean volume temperatures in the tank versus time calculated using simplified (balanced) method and obtained as a numerical simulation result was carried out.

Of special note is the paper [7] which presents the study of circulatory heating of oil in a tank with a floating lid. When carrying out numerical studies, the $k$-$\varepsilon$ turbulence model was used. For practical use, engineers are advised to adjust the spraying temperature and outflow velocity from the nozzle taking into account the Froude number.

The difficulty of carrying out the experiment for studying the circulatory heating of fuel explains the small base of experimental data on this topic. The main experimental data on the natural cooling and heating of fuel oil on the industrial scale for tanks of various volumes were obtained by Z.I. Geller [8 – 10].

Despite the widespread use of circulatory heating of fuel in the storage tanks as well as the need to
improve this method of adjusting the temperature regime, currently, there is a small number of works on this topic [7].

The aim of this work is to study the influence of the inclination angle of the nozzle on the circulatory heating process of the fuel oil in the RVS-3000 tank.

**The problem formulation of heat transfer at the laminar flow of fuel oil jet in the tank**

When formulating the mathematical model of heat transfer at the laminar flow of the fuel oil jet the following assumptions are made:

1. nonstationarity of heat transfer processes is determined by the time dependence of the fuel oil temperature in the storage tank;
2. thermophysical properties of fuel oil such as density $\rho$, heat capacity $c_p$, thermal conductivity $\lambda$, and kinematic viscosity of fuel oil $v$ depend on the temperature $T$;
3. volume force influencing on the flow process of the fuel oil jet from the nozzle has the form:

$$\vec{F} = \alpha g \rho \left( T - T_{fueloil} \right),$$

where $\alpha = \frac{\rho_{oil} \rho_o}{\rho_o (T_o - 293)}$ – coefficient of volume expansion, 1/K; $g$ – acceleration of gravity, m/s$^2$; $T_{fueloil}$ – fuel oil temperature at the nozzle outlet, K;
4. rheological behavior of fuel oil is Newtonian.

The primary system of equations is based on the fundamental differential equation system of energy conservation and continuum mechanics – equations of motion and continuity.

Since the supply manifolds in the fuel oil storage tanks in most cases have closely spaced nozzles the single jets flowing out of them can be replaced by a single plane jet flowing out of the plane-slot nozzle. Mathematically, this approximation allows reducing the three-dimensional formulation of the problem of heat transfer to the two-dimensional axisymmetric problem.

The geometric domain for determining the unknown variables of the problem for the fuel oil jet is shown in Fig. 1.

![Geometric domain of fuel oil jet flow in the tank](image)

**Fig. 1.** The geometric domain of fuel oil jet flow in the tank

Because of the symmetry of the problem the flow is considered in the plane $ABCDE$ where $r$ – the coordinates of points $C$ and $D$, $z$ – the coordinates of points $B$ and $C$, $\delta$ – outlet of the $AE$ tank, $h_r$ – radius $AD$ and $BC$ of the studied area, $h_z$ – height $AB$ and $DC$ of the studied area, $\alpha$ – inclination angle of the nozzle.
Modeling of heat transfer at a laminar flowing of a fuel oil jet

The initial system of equations of motion and energy transfer describing the heat transfer process at flowing of a fuel oil jet in the general tensor formulation for the accepted assumptions has the form:

\[
\rho c_p \frac{dT}{dt} = \text{div}(\lambda \text{grad} T),
\]

\[
\frac{d\vec{V}}{dt} = \frac{1}{\rho} \text{div} \vec{T} + \vec{f},
\]

\[
\frac{\partial P}{\partial t} + \text{div} \vec{V} = 0,
\]

where \( \vec{T} \) – stress tensor.

We write down the initial and boundary hydrodynamic and thermal conditions at flowing of fuel oil jet to close this system of equations.

The initial hydrodynamic condition has the form:

\[
\vec{V}(t = 0) = \vec{V}_0.
\]

The initial temperature condition has the form:

\[
T(t = 0) = T_0.
\]

The hydrodynamic boundary conditions:

– the velocity profile corresponding to the formed velocity profile of the Newtonian fluid in the circular pipe is specified at the inlet opening;
– at the outlet – condition of the fluid flow stabilization;
– the no-slip conditions of the fluid are specified at the solid and open boundaries of the tank.

Thermal boundary conditions:

– second-type boundary conditions – environmental heat losses – are specified at the solid and open boundaries;
– at the tank outlet we accept the predominance condition of the heat flow due to the convection compared to the heat flow due to the thermal conductivity in a direction perpendicular to the boundary;
– the temperature of the hot fuel oil fed to the tank is specified at the inlet.

The reliability of the mathematical model and the solution method was verified by comparison with the experiment results of the Z.I. Geller for circulatory heating of the cracking residues [11].

Results of numerical studies

The heating of the M100 fuel oil in the RVS-3000 tank was considered in this paper. Geometric characteristics of the tank: the diameter at the base \( D = 18.98 \) m, the height \( H = 11.82 \) m, the thickness of the tank steel walls \( \delta_1 = 0.008 \) m, the thickness of the tank walls insulation (mineral wool mats) \( \delta_2 = 0.07 \) m, the thickness of the tank aluminum coating \( \delta_3 = 0.0005 \) m, the volume at the maximum operating level \( V = 3340 \) m³. The thickness of the concrete pad \( \delta = 1.5 \) m, the height of the fuel oil layer in the tank \( h = 10.7 \) m. The diameter of the nozzle exit section \( d = 12 \) mm, the height of location above the tank bottom \( h_k = 0.3 \) m. The nozzle inclination relative to the horizontal and vertical planes in the classical version is \( \alpha = -10^\circ \). The supply manifold diameter \( D_k = 5 \) m.

The winter storage period of fuel oil in the RVS-3000 tank for Kazan was considered. The average ambient temperature for winter is 13.5 °C (January). Fuel oil in the tank is stored in the cold standby
mode at $t_{\text{cold}} = 30^\circ \text{C}$.

Numerical studies of various inclination angles of the nozzle relative to the horizontal plane $\alpha = 40\ldots-40^\circ$ in increments of $10^\circ$ were carried out. The fuel oil flow rate was specified as $G_h = 60 \text{ t/h} (16.67 \text{ kg/s})$ which is equal to productivity of the fuel oil heater PM-10-60. The fuel oil temperature at the outlet of the fuel oil heater is $t_{\text{jet}} = 115^\circ \text{C}$. The results of numerical studies of the tank heating time in winter period are shown in Fig. 2.

![Fig. 2. The heating time of fuel oil in the RVS-3000 tank in winter period](image)

During the first 20 hours of heating, the mean volume temperature in the tank for all inclination angles of the nozzle is practically the same. After 100 hours of heating, the mean volume temperature for inclination angles of the nozzle $\alpha = -20\ldots-40^\circ$ is lower by $1.6 – 6.8^\circ \text{C}$ compared to the classical arrangement of the nozzle. The best heating is observed for angles higher than $\alpha = -10^\circ$.

![Fig. 3. The heating time of fuel oil in the RVS-3000 tank in the winter period](image)

Fig. 3 shows the comparison of the fuel oil heating time in the RVS-3000 tank in the winter period up to the specified temperatures: $60^\circ \text{C}$ (the hot storage temperature) and $90^\circ \text{C}$ (fuel oil temperature before feeding to the nozzles for combustion).

The inclination angle of the nozzle practically does not influence the heating up to the hot storage
temperature in the tank of 60 °C. The optimum nozzle angle for fuel oil heating before feeding to the nozzles for combustion is $\alpha = -10...40^\circ$.

**Conclusions**

Change of the inclination angle of the nozzle in the range of $-20^\circ$ to $-40^\circ$ is inadvisable since a longer period of time is required for heating the tank due to an increase of heat losses through the tank bottom. Change of the inclination angle of the nozzle is advisable in the range of $-10^\circ$ to $40^\circ$ since a smaller period of time is required for heating the tank.

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