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ESTIMATION OF THE CONVECTION HEAT EXCHANGE RATE FOR TANK SHELLS COVERED WITH FALLING WATER FILM

The methods of similarity theory were used to identify the convection heat exchange rate for tank shells covered with the falling water film generated by spray distribution rings. Dependencies of the film thickness and its falling rate on the water flow rate are provided herein.

Keywords: *tank, fire, convection heat exchange, forced convection, water film*

Problem statement. The main hazard of fire in the oil-product tank batteries lies in the tank battery heating due to thermal influence that fire makes. Certain elements of the tank structure can be heated to the spontaneous ignition temperature of the vapors exhaled by the contained oil products, and that can cause inflammation of vapors at the pressure vent valves of the tank or explosion in the vapor space of the tank. For this very reason tank cooling is the key issue to be solved for fire containment at the oil-product tank batteries. One of the options for tank shell cooling in case of fire is using fixed spray distribution rings.

Analysis of the recent researches and publications. The study [1] is based on analysis of the model of heat influence that fire in the tank makes on the adjacent oil-product tank. The model anticipates radial and convection heat exchange. Besides, the study is purposed at defining optimal dislocation of the fire-fighting hoses for cooling

[1] Y.A. Abramov, A.E. Basmanov. Emergency mitigation and recovery in the oil-product tank batteries. – Kharkiv: AGZU, 2006. – 256 pages.

of tanks that are not caught by fire. Herewith, it is assumed that the water flow rate of the fire-fighting hoses ensures sufficient level of cooling; though selection of the proper flow rate is made based on the regulatory documents only. The study [2] describes the trial of the scaled-down tank shell model (cooling area: 0.25 m^2) and the fire-fighting hose (nozzle diameter: 13 mm, water consumption: 4 l/s) and provides estimation of the rate of convection heat exchange between the tank shell and the falling water film. However, water spay cooling is peculiar for splashing of sufficient part of water from the tank shell (up to 80% [3]) and uniformity of the water film being formed. That makes accepting the results of study [2] directly to the case of applying the spray distribution rings impossible.

Paper objective. Purpose of the study is defining the rate of convection heat exchange between the tank shell and the falling water film formed by the spray distribution rings.

Paper main body. The Reynolds number for the water film falling down the vertical shell due to gravitational pull is defined using the following formula:

$$\mathrm{Re} = \frac{G}{\mu_c},$$

where G is the mass flow rate per the film width unit ($kg/m \cdot s$) and μ is the fluid dynamic viscosity ($Pa \cdot s$). Considering interrelation between the mass flow rate G and the flow delivery rate I,

$$G = I\rho_c,$$

where ρ_c is the water density, the following equation is generated:

[2] Y.A. Abramov. Simulation of fires, their detection, confinement and extinguishing / Y.A. Abramov, A.E. Basmanov, A.A. Tarasenko. – Kharkiv: NUCPU, 2011. – 927 pages.
[3] A.E. Basmanov. Interaction between the water spray and the tank shell when being cooled down during the fire / A.E. Basmanov, A.A. Mikhaylyuk // Fire safety issues. – 2009. – No. 25. – pages 14 - 20.

$$\mathrm{Re} = \frac{I\rho_c}{\mu_c} = \frac{I}{\nu_c}, \qquad (1)$$

where ν_c is the fluid kinematic viscosity (m^2/s). Considering that water kinematic viscosity is $\nu_c = (0{,}3 \div 1{,}0) \cdot 10^{-6}\ m^2/s$ within the temperature range $T_c = (20 \div 100)\ ^oC$, with the flow rate of $I \geq 1{,}2 \cdot 10^{-3}\ m^2/s$ the Reynolds number will be:

$$\mathrm{Re} \geq 1200.$$

In study [5] the recommended critical value of the Reynolds number for the severe turbulent conditions of the film falling is $\mathrm{Re}_{cr} = 1200$. Thus, while cooling the tank shells with the help of the fixed spray distribution rings, the severe turbulent conditions of the water film falling are created.

Water film thickness is defined using the following formula:

$$\tilde{\delta} = \sqrt[3]{\frac{c_f \,\mathrm{Re}^2}{2(1 - \rho''/\rho_c)}}, \qquad (2)$$

where $\tilde{\delta} = \delta \left(\frac{g}{\nu_c^2} \right)^{1/3}$ is the numerical film thickness; g is the free-fall acceleration; c_f is the rate of the film friction against the tank shells; ρ'' is the gaseous medium density. Considering that the water density is 3 times higher than the air density, the formula (2) can be made simpler:

[5] V.N. Sokolov. Gas-liquid reactors / V.N. Sokolov, I.V. Domansky. – L.: "Mashinostroyeniye" (Machine-building), 1976. – 216 pages.

$$\tilde{\delta} = \sqrt[3]{\frac{c_f \operatorname{Re}^2}{2}};$$

$$\delta^3 \frac{g}{\nu_c^2} = \frac{c_f \operatorname{Re}^2}{2}.$$

The friction rate c_f is taken up as the ratio for the turbulent flow of the fluid across the plain surface [6]:

$$c_f = 0{,}0582 \operatorname{Re}^{-0,2}.$$

In such a case the formula for the water film thickness calculation is to look as follows:

$$\delta = \left(\frac{0{,}0582}{2} \frac{\nu_c^2}{g} \operatorname{Re}^{1,8} \right)^{1/3} = 0{,}308 \left(\frac{\nu_c^2}{g} \right)^{1/3} \operatorname{Re}^{0,6}. \quad (3)$$

Plugging (1) into (3) results in the following formula:

$$\delta = 0{,}308 \frac{\nu_c^{2/3}}{g^{1/3}} \frac{I^{0,6}}{\nu_c^{0,6}} = 0{,}308 \frac{\nu_c^{2/3-0,6}}{g^{1/3}} I^{0,6};$$

$$\delta \cong 0{,}144 \nu_c^{0,067} I^{0,6}. \quad (4)$$

The study [6] describes the ratio between the water kinematic viscosity and its temperature as a table. This ratio can be approximated as an exponential function:

$$\nu_c = 3{,}16 \cdot 10^{-4} \left(\frac{T_c}{100} \right)^{-5,3489}, \quad (5)$$

[6] Heat engineering / [V.N. Lukanin, M.G. Shatrov, G.M. Kamfer, etc.]; edited by V.N. Lukanin. – M.: "Vysshaya Shkola" (Higher School), – 2002. – 671 pages.

where T_c is the water film temperature. The error of such approximation is to be no more than 7.5% within the temperature range of $T_c = (10 \div 100)\ ^oC$ (Fig. 1).

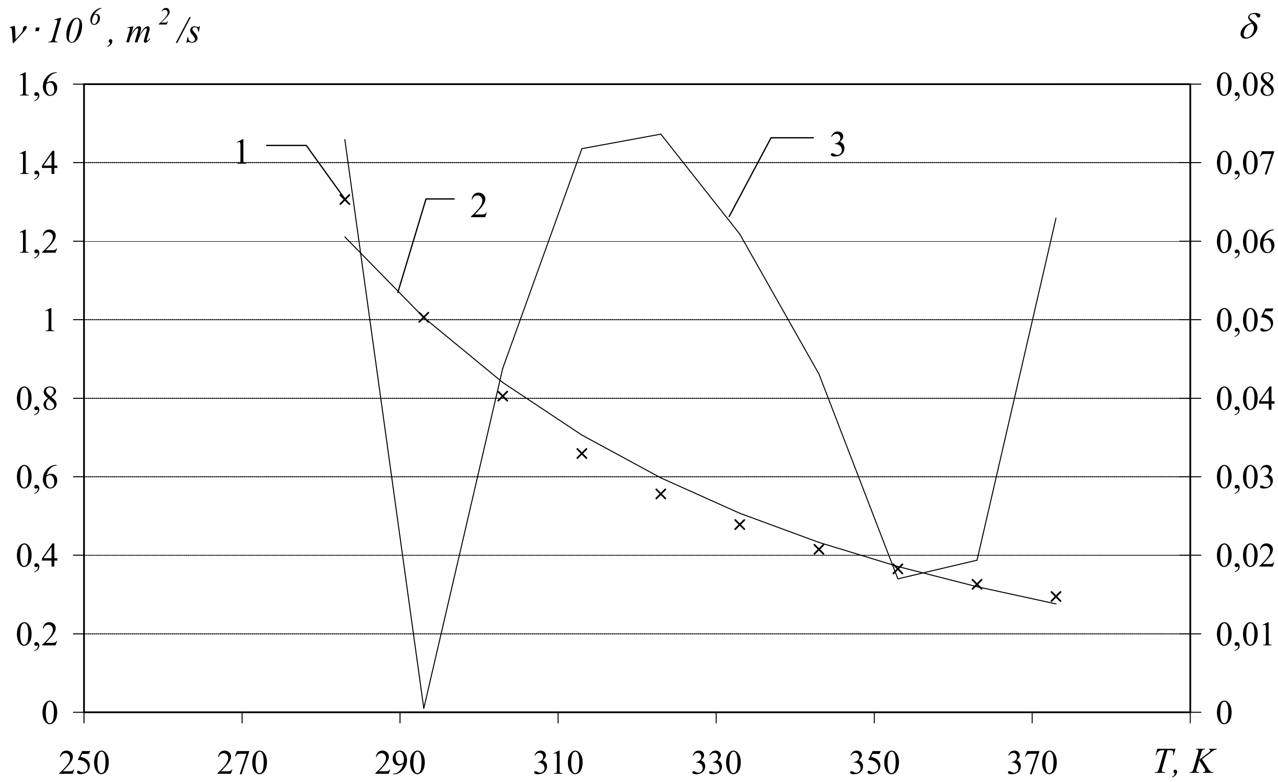

Fig. 1. Dependency of the water kinematic viscosity of the temperature: 1 – tabular data [6]; 2 – approximation for the formula (5); 3 – relative error (right axis)

Plugging approximation (5) into (4) makes the formula for the water film thickness calculation look as follows:

$$\delta \cong 0{,}437 T_c^{-0{,}358} I^{0{,}6}, \quad (6)$$

where all values are to be provided in SI units considering the dimension factors in (5), (6). Fig. 2 shows dependency of the water film thickness from its temperature and the water flow delivery rate set for cooling.

Analysis of the characteristic curve in Fig. 2 proves that when changing the water

[6] Heat engineering / [V.N. Lukanin, M.G. Shatrov, G.M. Kamfer, etc.]; edited by V.N. Lukanin. – M.: "Vysshaya Shkola" (Higher School), – 2002. – 671 pages.

flow delivery rate within the range of 1.2 $l/m \cdot s$ to 4 $l/m \cdot s$ the water film thickness increases from 1.0 mm to 2.1 mm. At the same time water temperature rising from 10 ^oC to 100^oC results in reduction of the water film thickness by just 10%.

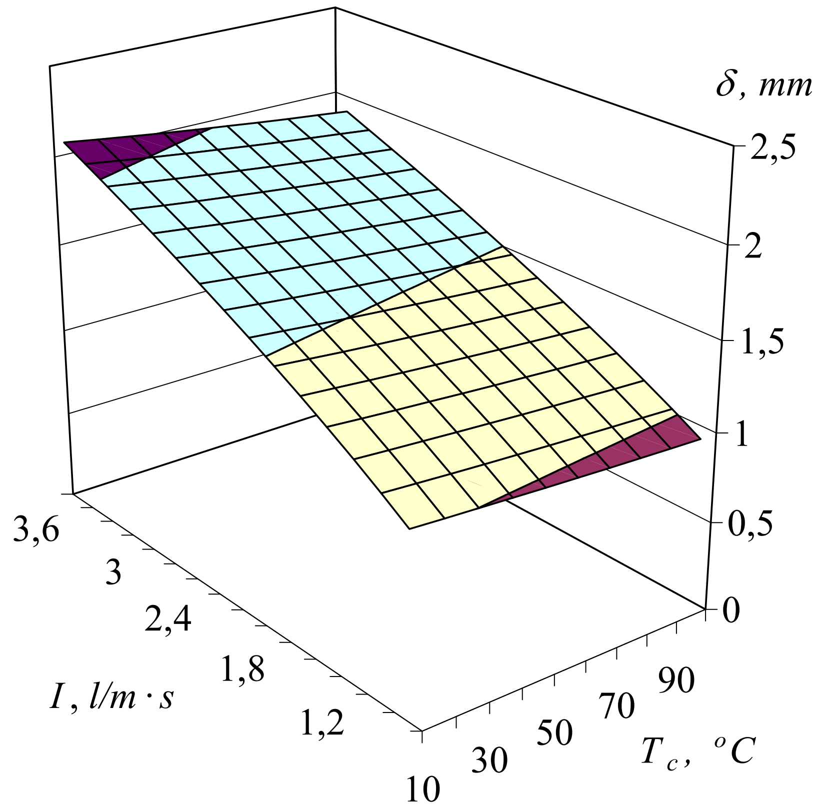

Fig. 2. Dependency of the water film thickness from its temperature and the water flow delivery rate

That means the formula (6) can be made simpler through plugging $T_c = 55^o C = 328\,K$ in:

$$\delta \cong 0{,}055 I^{0{,}6}. \quad (7)$$

Herewith, the error of such plugging in is to stay within 5%.

The water film falling rate w_c is defined by the following dependency:

$$w_c = \frac{I}{\delta} \cong 18{,}2 I^{0{,}4}. \quad (8)$$

The dependency analysis (8) proves that in order to keep the sprinkling intensity within the range of 1.2 $l/m \cdot s$ to 4 $l/m \cdot s$ the water film rate is to be defined by the formula $w_c = (1{,}2 \div 2{,}0)\, m/s$.

The rate of the convection heat exchange between the tank shell and the water film α_c can be defined using the following formula [4] :

$$\frac{\alpha_c}{\lambda_c}\left(\frac{\nu_c^2}{g}\right)^{1/3} = 0{,}023\,\mathrm{Re}^{0{,}25}\,\mathrm{Pr}^{0{,}5}, \qquad (9)$$

where λ_c is the thermal conductivity rate of water; Pr is the Prandtl number of water. Plugging (1) into (9) makes the last formula look as follows:

$$\frac{\alpha_c}{\lambda_c}\left(\frac{\nu_c^2}{g}\right)^{1/3} = 0{,}023\left(\frac{I}{\nu_c}\right)^{0{,}25}\mathrm{Pr}^{0{,}5};$$

$$\alpha_c = 0{,}023\lambda_c \frac{g^{1/3}}{\nu_c^{2/3+0{,}25}}\mathrm{Pr}^{0{,}5}\, I^{0{,}25}. \qquad (10)$$

Considering that such water properties as kinematic viscosity ν_c, thermal conductivity rate λ_c and the Prandtl number Pr depend on the temperature [6], the formula:

$$f_1(T_c) = 0{,}023\lambda_c \frac{g^{1/3}}{\nu_c^{2/3+0{,}25}}\mathrm{Pr}^{0{,}5} \qquad (11)$$

can be replaced with the linear function:

[4] M.A. Mikheyev. Heat transfer principles / M.A. Mikheyev, I.M. Mikheyeva. – M.: "Energiya" (Energy), 1997. – 344 pages.
[6] Heat engineering / [V.N. Lukanin, M.G. Shatrov, G.M. Kamfer, etc.]; edited by V.N. Lukanin. – M.: "Vysshaya Shkola" (Higher School), – 2002. – 671 pages.

$$\tilde{f}_1(T_c) = 238{,}53T_c - 45098. \quad (12)$$

Approximation error (12) is to be no more than 4% within the temperature range of $T_c = (10 \div 100)\ ^oC$ (Fig. 3).

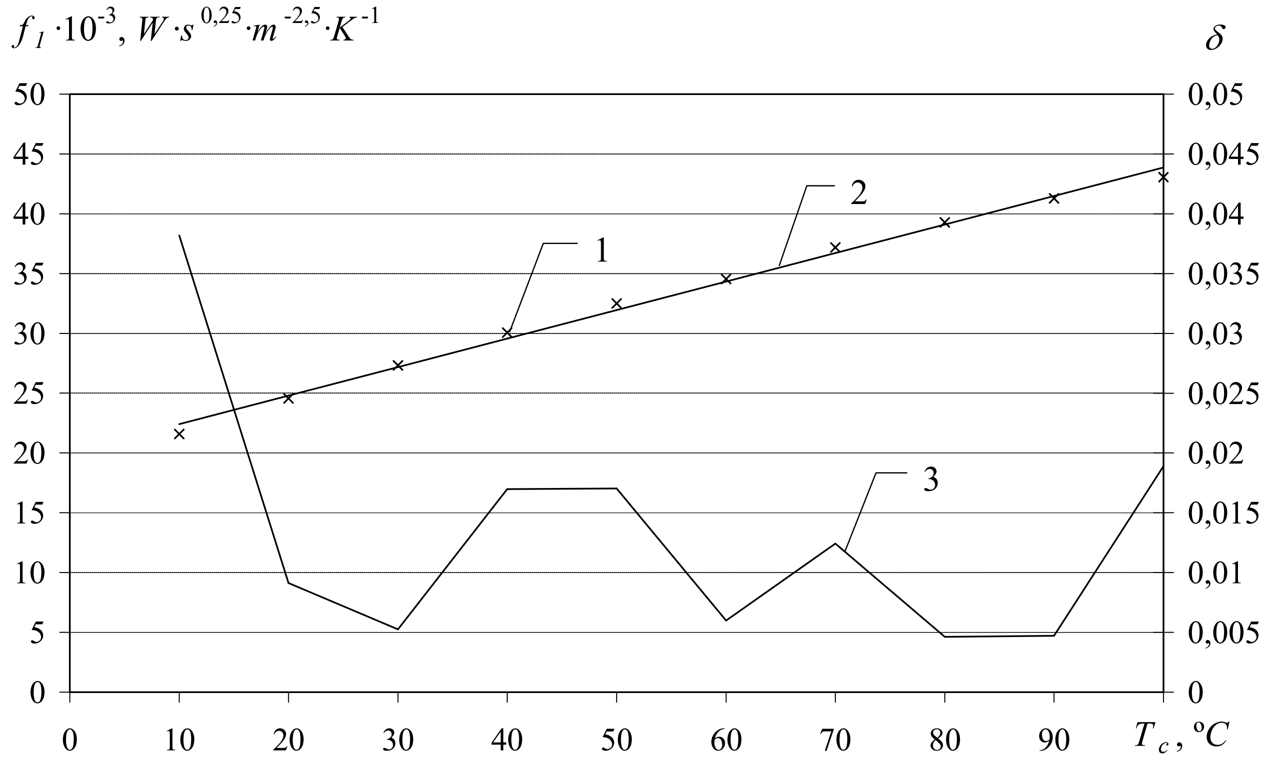

Fig. 3. Dependency of the water film temperature: 1 – $f_1(T_c)$; 2 – approximation $\tilde{f}_1(T_c)$; 3 – relative approximation error

Plugging the linear function (12) into (10) instead of (11) allows calculating the convection heat exchange rate as follows:

$$\alpha_c = (238{,}53T_c - 45098)I^{0,25}. \quad (13)$$

Fig. 4 shows dependency of the rate of convection heat exchange with the water film α_c from its temperature T_c and the water flow delivery rate I during the cooling process.

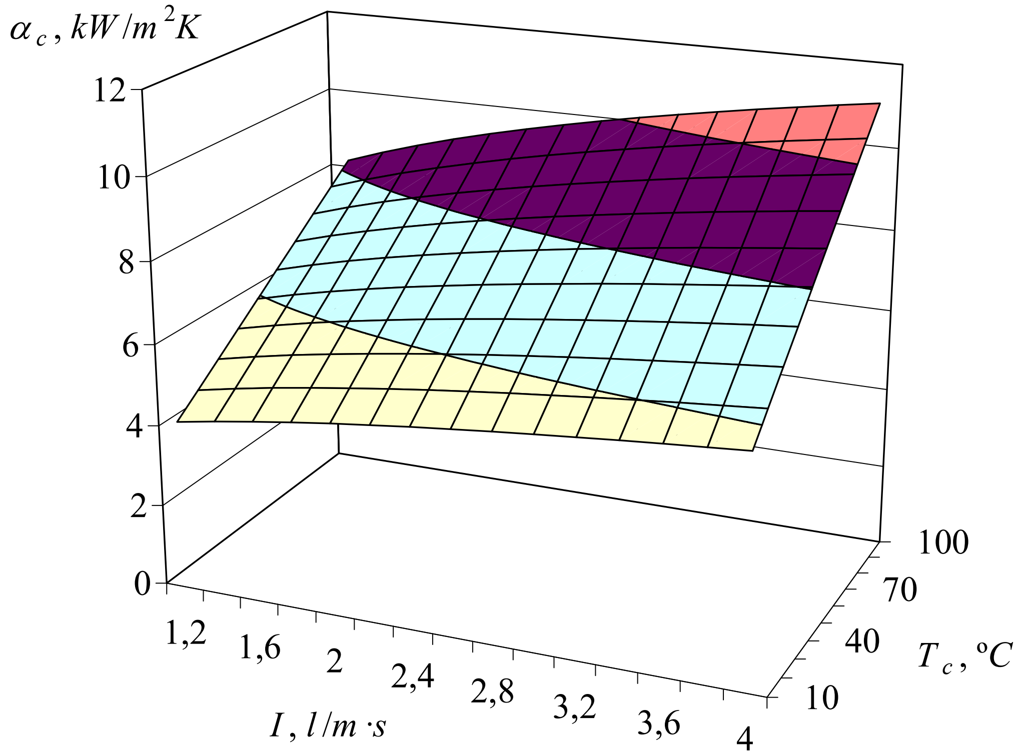

Fig. 4. Dependency of the rate of convection heat exchange with the water film from its temperature and the water flow delivery rate

Analysis of the comparison of (13) and Fig. 4 proves that within the water film temperature range $T_c = (10 \div 100)\ ^oC$ and the range of the water flow delivery rates $I = (1{,}2 \div 4{,}0)\, l/m \cdot s$ the heat exchange rate belongs to the range $(4{,}2 \div 11{,}0)\, kW/m^2K$. Herewith, dependency $\alpha_c(T_c, I)$ is of almost linear character.

Conclusions. The rate of the convection heat exchange between the tank shell and the water film formed by the spray distribution rings has been estimated. The study shows that the water film thickness is proportionate to $I^{0,6}$, the falling rate is $I^{0,4}$, the convection heat exchange rate is $I^{0,25}$, where I is the sprinkling intensity. The obtained results can be used while generating the tank cooling model for fire conditions.

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SIMULATION MODELS APPLICATION FOR SAFETY LEVEL MONITORING AND FORECASTING OF WASTES STORAGE PLACE

Abstract: *The main result is improvement of the safety level forecasting method for wastes storage place on the basis of simulation modeling application for safety management system functioning. Parameters needed for safety level assessment of the wastes storage place, which determine extreme situations occurrence risk, and environmental quality indexes are represented as responses on external factors influence. Interrelations of the process taking place on the object and in the environment are stated and represented in formalized way.*

Keywords: *forecasting, safety level, simulation modeling, wastes, extreme situation.*