ESTIMATION OF THE CONVECTIVE HEAT TRANSFER COEFFICIENT FOR TANK SHELL COVERED WITH FALLING WATER FILM

O.E. Basmanov[1], *Y.S. Kulik*[1]

[1] National University of Civil Protection of Ukraine, Ukraine

Abstract

The methods of similarity theory were used to identify the convective heat transfer coefficient for tank shell 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, convective heat transfer, forced convection, water film

1. Introduction

The main hazard of fire in the oil depots lies in the tank heating due to thermal influence that fire makes. Certain elements of the tank structure can be heated to the autoignition temperature of the vapors exhaled by the contained oil products, and that can cause inflammation of vapors at the vent valves of the tank or explosion in the vapor space of the tank. The work [1] contains historical survey of fire and explosions in the hydrocarbon industry. Tank cooling is the key issue to be solved for tank or dike fires. One of the options for tank shell cooling is using fixed spray distribution rings.

The study [2] 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 thermal radiation and convective heat transfer. Besides, the study is purposed at defining optimal dislocation of the fire-fighting hoses for cooling the nearby tanks. 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 [3] 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 convective heat transfer coefficient 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% [4]) and uniformity of the water film being formed. That makes accepting the results of study [3] directly to the case of applying the spray distribution rings impossible.

2. Results and Discussion

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 relation 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:

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

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

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

The recommended critical value of the Reynolds number for the severe turbulent conditions of the film falling is $\mathrm{Re}_{cr} = 1200$ [6]. Thus, while cooling the tank shell with the fixed spray distribution rings, the severe turbulent conditions of the water film falling are created.

Water film thickness is defined using the 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 dimensionless film thickness; g is the gravitational acceleration; c_f is the rate of the film friction against the tank shell; ρ'' is the ambient air density. Considering that the water density is 3 times higher than the air density, the formula (2) can be made simpler:

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

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

The friction rate c_f is taken up as the ratio for the turbulent flow of the fluid across the plain surface [7]:

$$c_f = 0.0582\, Re^{-0.2}.$$

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

$$\delta = \left(\frac{0.0582}{2} \frac{\nu_c^2}{g} Re^{1.8}\right)^{1/3} = 0.308 \left(\frac{\nu_c^2}{g}\right)^{1/3} Re^{0.6}. \qquad (3)$$

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

$$\delta = 0.308 \frac{\nu_c^{2/3}}{g^{1/3}} \frac{I^{0.6}}{\nu_c^{0.6}} = 0{,}308 \frac{\nu_c^{2/3-0.6}}{g^{1/3}} I^{0.6};$$

$$\delta \cong 0.144 \nu_c^{0.067} I^{0.6}. \qquad (4)$$

The study [7] describes the ratio between the water kinematic viscosity and its temperature as a table. This ratio can be approximated as an exponential function:

$$\nu_c = 3.16 \cdot 10^{-4} \left(\frac{T_c}{100}\right)^{-5.3489}, \qquad (5)$$

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).

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

$$\delta \cong 0.437 T_c^{-0.358} I^{0.6}, \qquad (6)$$

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 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 $10^o C$ to $100^o C$ results in reduction of the water film thickness by just 10%.

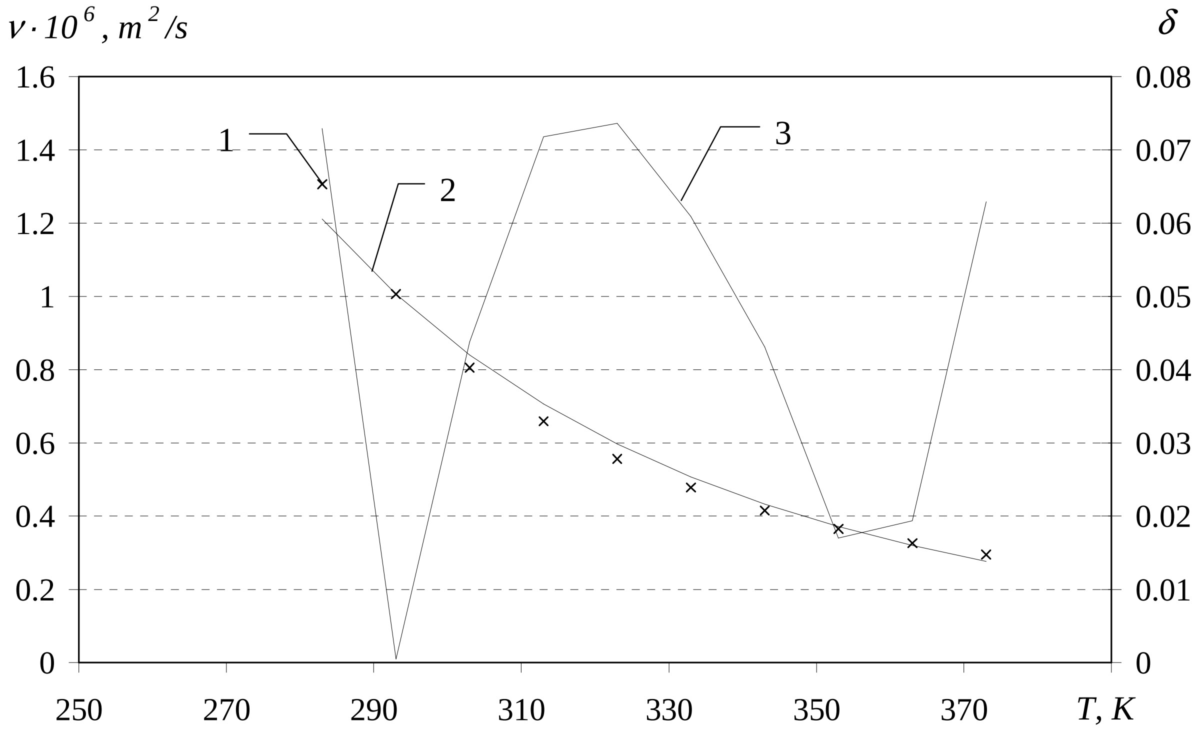

Fig. 1. Dependency of the water kinematic viscosity of the temperature: 1 – tabular data [7]; 2 – approximation for the formula (5); 3 – relative error (right axis)

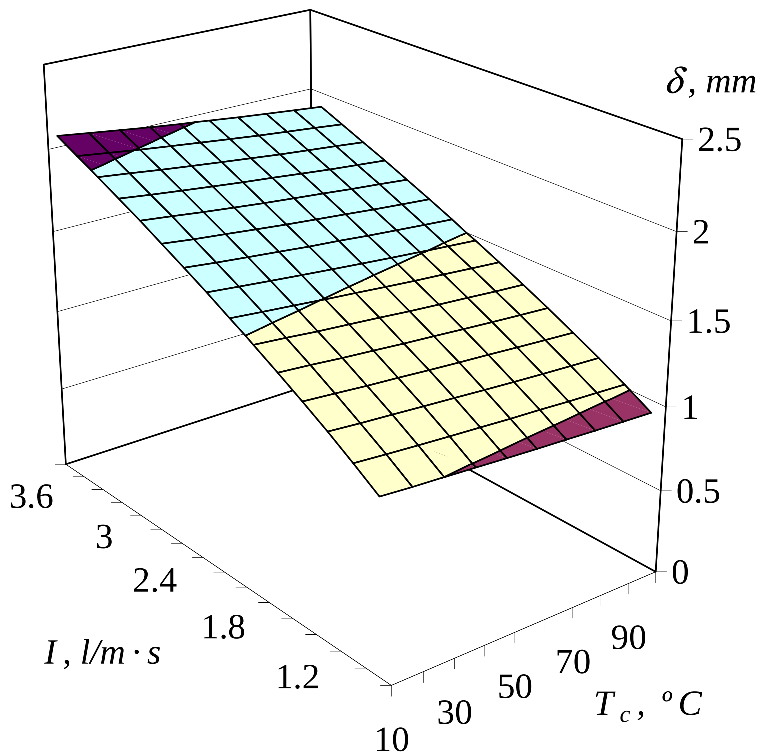

Fig. 2. Dependency of the water film thickness from its temperature and the water flow delivery rate

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

$$\delta \cong 0.055 I^{0,6}. \tag{7}$$

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:

$$w_c = \frac{I}{\delta} \cong 18.2 I^{0.4}. \tag{8}$$

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 convective heat transfer coefficient between the tank shell and the water film α_c can be defined using the following formula [5] :

$$\frac{\alpha_c}{\lambda_c}\left(\frac{\nu_c^2}{g}\right)^{1/3} = 0.023 Re^{0.25} Pr^{0.5}, \tag{9}$$

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:

$$\frac{\alpha_c}{\lambda_c}\left(\frac{\nu_c^2}{g}\right)^{1/3} = 0{,}023\left(\frac{I}{\nu_c}\right)^{0.25} Pr^{0.5};$$

$$\alpha_c = 0.023 \lambda_c \frac{g^{1/3}}{\nu_c^{2/3+0.25}} Pr^{0.5} I^{0.25}. \tag{10}$$

Considering that such water properties as kinematic viscosity ν_c, thermal conductivity rate λ_c and the Prandtl number $\Pr$ depend on the temperature [7], the formula:

$$f_1(T_c) = 0{,}023 \lambda_c \frac{g^{1/3}}{\nu_c^{2/3+0.25}} Pr^{0,5} \tag{11}$$

can be replaced with the linear function:

$$\tilde{f}_1(T_c) = 238.53 T_c - 45098. \tag{12}$$

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

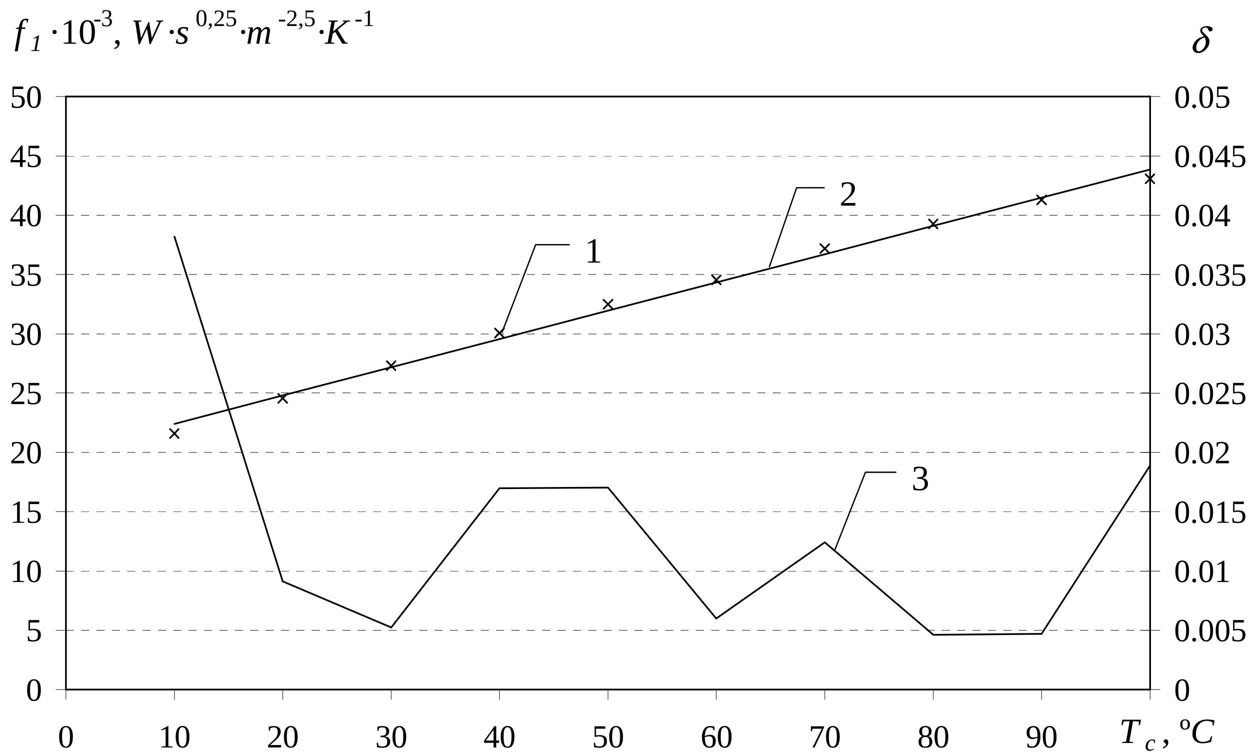

Fig. 3. Dependency of the water film temperature: 1 – $f_1(T_c)$; 2 – approximation $\tilde{f}_1(T_c)$; 3 – relative approximation error

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

$$\alpha_c = (238.53T_c - 45098)I^{0.25}. \qquad (13)$$

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

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 transfer coefficient belongs to the range $(4.2 \div 11.0)\ kW/m^2K$. Herewith, dependency $\alpha_c(T_c, I)$ is of almost linear character.

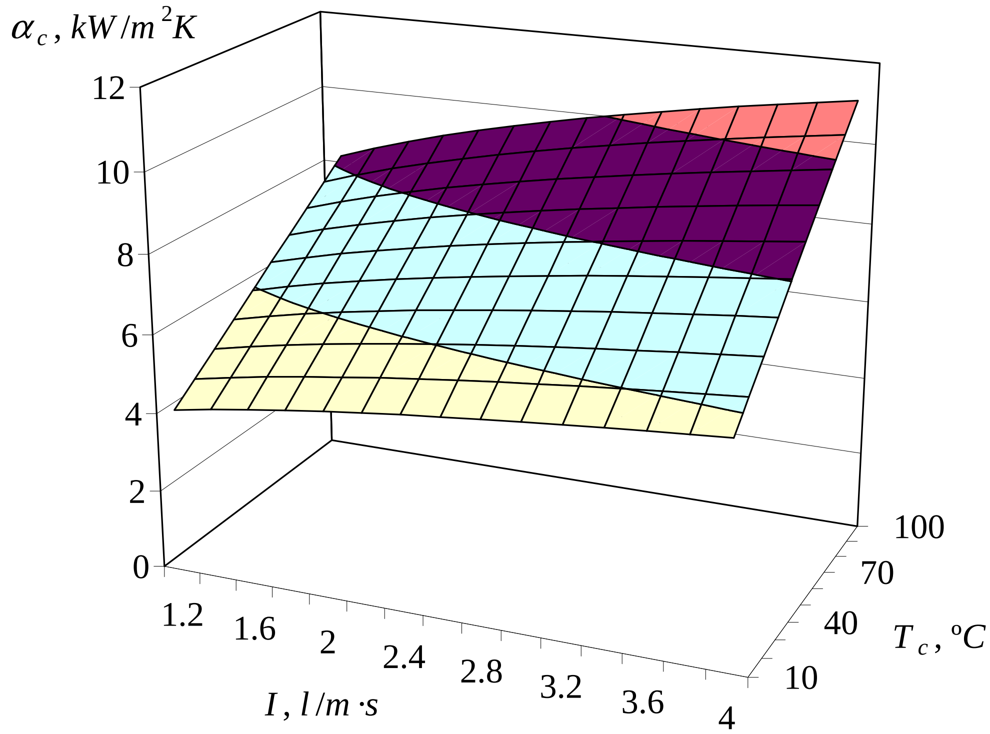

Fig. 4. Dependency of the convective heat transfer coefficient with the water film from its temperature and the water flow delivery rate

3. Conclusions

The convective heat transfer coefficient 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 convective heat transfer coefficient is $I^{0.25}$, where I is the sprinkling intensity. The obtained results can be used while generating the tank cooling model in case of fire.

References

[1] Nolan, D.P. (2010). *Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical, and Related Facilities*. Burlington, MA: William Andrew Publishing.

[2] Abramov, Y.A., Basmanov, O.E. (2006). *Emergency mitigation and recovery in the oil depots*. Kharkiv: Academy of Civil Protection of Ukraine.

[3] Abramov, Y.A., Basmanov, O.E., Tarasenko, A.A. (2011). *Simulation of fires, their detection, localization and extinguishing*. Kharkiv: National University of Civil Protection of Ukraine.

[4] Basmanov, O.E., Mikhaylyuk, A.A. (2009). Interaction between the water spray and the tank shell when being cooled down during the fire. *The problems of fire safety, 25*, 14-20. Retrieved from http://repositsc.nuczu.edu.ua/handle/123456789/304

[5] Mikheyev, M.A., Mikheyeva, I.M. *Heat transfer principles*. (1997). Moscow: Energiya.
[6] Sokolov, V.N., Domansky, I.V. *Gas-liquid reactors*. (1976). Leningrad: Mashinostroyeniye.
[7] Lukanin, V.N., Shatrov, M.G., Kamfer, G.M., etc. (2002). *Heat engineering*. Moscow: Vysshaya Shkola.