Evaporation of a Water-Alcoholic Solution Drop in a High-Temperature Air Flow

Boris V. Borisov[a)], Ruslan T. Zakiev and Alexander S. Naumkin

National Research Tomsk Polytechnic University, 634050, Tomsk, Russia.

[a)]Corresponding author: bvborisov@tpu.ru

Abstract. In this work, we present the analyses results of an aqueous-alcoholic solution drop evaporation in a high-temperature air flow. On the analysis basis, a simplified mathematical model of the process is formulated. The comparative analysis results of physical experiments and mathematical modeling of the processes under study are presented.

INTRODUCTION

The interaction of high-temperature air flow with a drop of water-alcohol processes are encountered when considering technologies for the disposal of industrial waste and methods of using alcohols as an energy fuel, albeit with a higher alcohols concentration. Increasing the industrial technologies efficiency requires, at the preliminary designing appropriate systems stage, reliable experimental main data on the processes parameters for the formulation of mathematical models that allow, in the numerical modeling process, to reduce material and time costs when creating final structures [1,2].

This purpose of this work is to determine the main parameters of the evaporation process of a water-ethanol solution drop with various concentrations in a high-temperature air flow and to formulate the with good predictive capabilities process mathematical model, based on the of experimental results.

EXPERIMENTAL METHOD

The measurements of the process parameters of were carried out on the installation, which is schematically shown in (Fig. 1) [3].

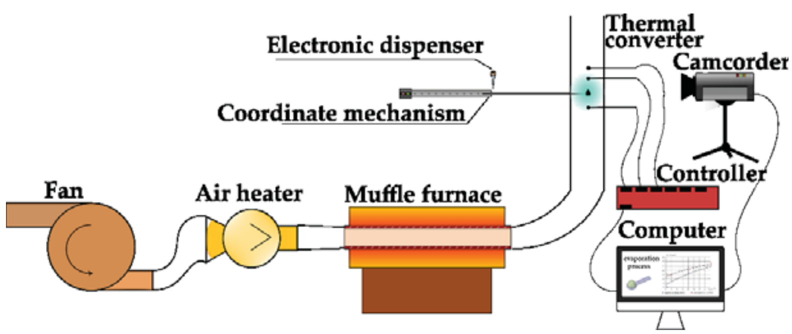

FIGURE 1. Laboratory stand scheme

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The installation consists of a high-pressure fan AIRPACK 119.358, an air heater LHS 61L Premium with a power of 16 kW, a Novaterm RT1145.1200 furnace with a power of 14 kW, a quartz tube with an inner diameter of 95 mm, thermoelectric converters (TC) DTPK031-0.5/0.2/1, a video camera Phantomv411, temperature measurement and control devices UKT38 and personal computer.

The Phantom V411 video camera with a frame rate of 4200 fps and a resolution of 1280x800 pixels and the "TemaAutomotive" software package allow us to view the results frame-by-frame to determine the droplet evaporation rate.

The air passed through the air heater and through the furnace and is heated to the set temperature. Further, the air with an average flow rate of 4.23 m/s passed in a quartz tube. The solution drop with an initial temperature of 20 ˚C by a coordinating mechanism moved at a constant speed into the flow from the edge and is carried out to the center of the pipe within 2 seconds.

Electrical signals from thermoelectric converters (TC) entered the UKT38 controller and after processed via the RS-232 communication interface to a computer, where the determination of temperature characteristics was processed used the LabVIEW software package.TC were located along the flow. The first thermoelectric converter (TC1) placed before the drop and another two (TC2, TC3) placed after the drop at the same distance of 5 mm from each other.

The error analysis was carried out with a confidence level of 95 %.

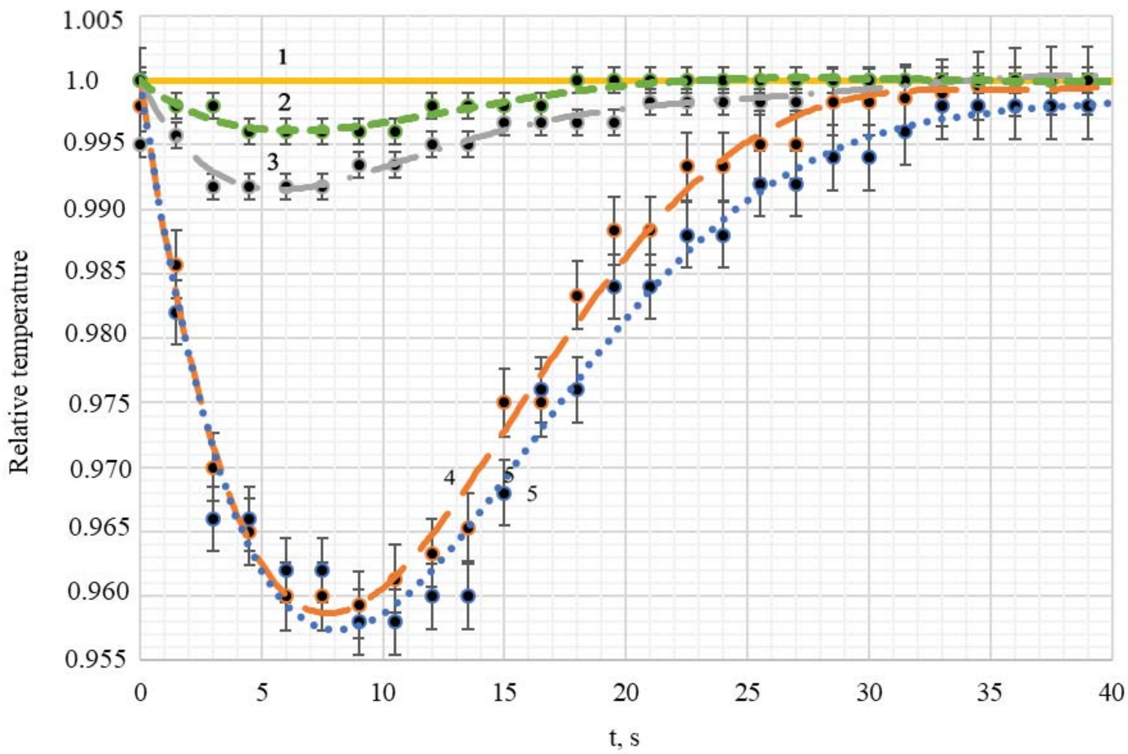

FIGURE 2. Variation of the dimensionless temperature (Θ) in time when air flows around a droplet with an ethanol concentration in the solution of 10% for an incident flow temperature of 500 °C (curves 1, 2, 3) and 600 °C (curves 1, 4, 5)

The numbers indicate the readings of the thermal converters: 1 – TC1, 2 – TC2, 3 – TC3; 4 – TC2, 5 – TC3

$$\Theta = \left(t - t_g\right) / \left(t_0 - t_g\right) \tag{1}$$

Where t – is the measured temperature, t_0 – is the initial temperature of the drop, t_g – is the temperature of the incoming flow.

Analysis of temperature changes Θ over time (Fig. 2) shows that the drops TC2 and TC3 falling into the vapor cloud have a noticeable temperature minimum in their measurements, while the temperature according to the TP1 readings does not change over time. This may indicate the constant removal of vapors from the surface of the droplet by the air flow. In this case, the evaporation process proceeds in a kinetic mode, and the evaporation rate is determined exclusively by the process of heat transfer from air to the drop.

By processing the image of the drop in time, the characteristic diameter was determined, the change of which was approximated by a polynomial (Fig. 3).

This approach makes it possible by differentiating the obtained polynomial to determine the dependences of the rate of the drop in time under the assumption that the process is monotonic.

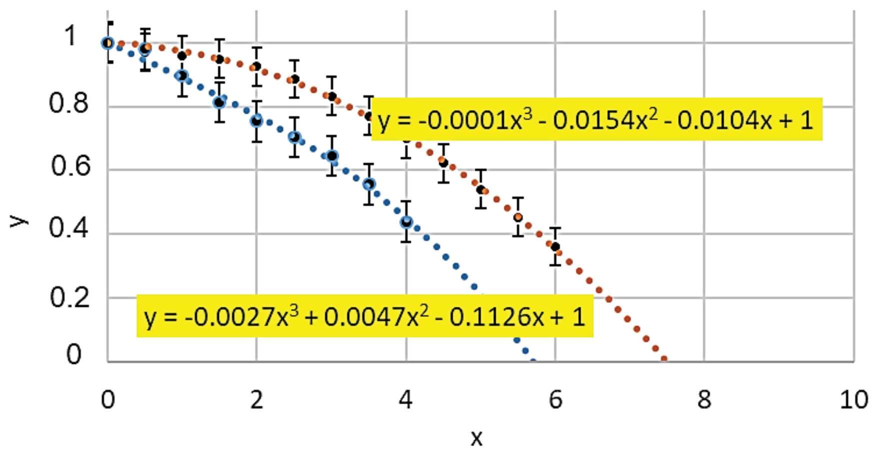

FIGURE 3. Variation of the dimensionless droplet radius (y) versus time (x).
······ – incident flow temperature of 600 °C, ······– incident flow temperature of 500 °C

THEORETICAL METHOD

The kinetic regime of droplet evaporation determined by analyzing the temperature field around the droplet gives grounds to write the following relation:

$$\alpha\left(t_g - t_s\right) = q_s \rho W \tag{2}$$

Where α, t_s, q_s, ρ, W – are heat transfer coefficient, droplet temperature, heat of vaporization, droplet solution density and rate of change in droplet radius.

Heat transfer in a forced flow around a ball according to [4, 5] is determined by the empirical formula:

$$\mathrm{Nu} = 2 + 0.03\,\mathrm{Re}^{0.54}\,\mathrm{Pr}^{0.33} + 0.35\,\mathrm{Re}^{0.58}\,\mathrm{Pr}^{0.36} \tag{3}$$

As the analysis showed, the influence on the heat transfer coefficient by the steam entering the boundary layer, carried out in accordance with the proposal of V.P. Mugalev [6], can be neglected. The heat of vaporization is determined in accordance with the additive law for the mass fractions of the droplet components.

The change in the radius of the drop R and in time τ taking into account the change in the mass fraction of alcohol g_1 is determined by the system of ordinary differential equations:

$$\begin{aligned} &\frac{dR}{d\tau} = -W \\ &\frac{d\left(\rho R^3\right)}{d\tau} = -\rho W 3R^2 \\ &\frac{d\left(g_1 \rho R^3\right)}{d\tau} = -g_{1s} \rho W 3R^2 \end{aligned} \tag{4}$$

The determination of the mass fraction of alcohol in the vapor flow was carried out using the ratio including the molecular weights of the components (M_i) and saturated vapor pressures at the droplet temperature (p_{is}):

$$g_{1s} = \frac{M_1 p_{1s}}{M_1 p_{1s} + M_2 p_{2s}} \tag{5}$$

The evaporating droplet temperature was taken to be equal to the boiling point of the component with the largest mass fraction. As shown by preliminary estimates, TC1 placed in front of the drop had a disturbing effect on the flow and increased the heat transfer coefficient by 15 % – 20 %. This is consistent with the results of the heat transfer coefficients analysis of the in the tube bundle in-line type [1].

The presented mathematical model describes very approximately the complex processes of evaporation of two-component systems. However, it has the ability to satisfactorily assess the main characteristics of the evaporation process at the first preliminary stage of the study. To prove this statement, “ANALYSIS OF RESULTS” was carried out.

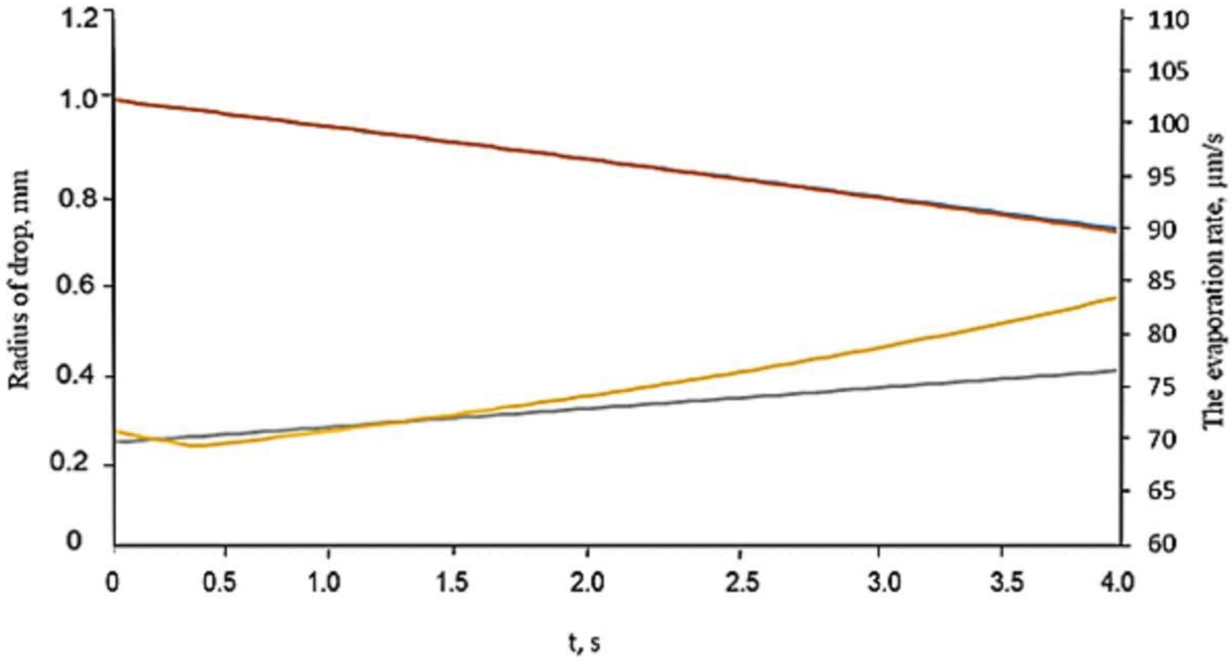

FIGURE 4. Dynamics of the change in the radius of a drop of a 5 % ethanol solution and the modulus of its rate of change versus time at an incoming air flow temperature of 600 °C; droplet radius (experiment- 2degree polinomial), mm; droplet radius (mathematical model), mm; the evaporation rate (experiment- 2degree polinomial), µm/s; the evaporation rate (mathematical model), µm/s

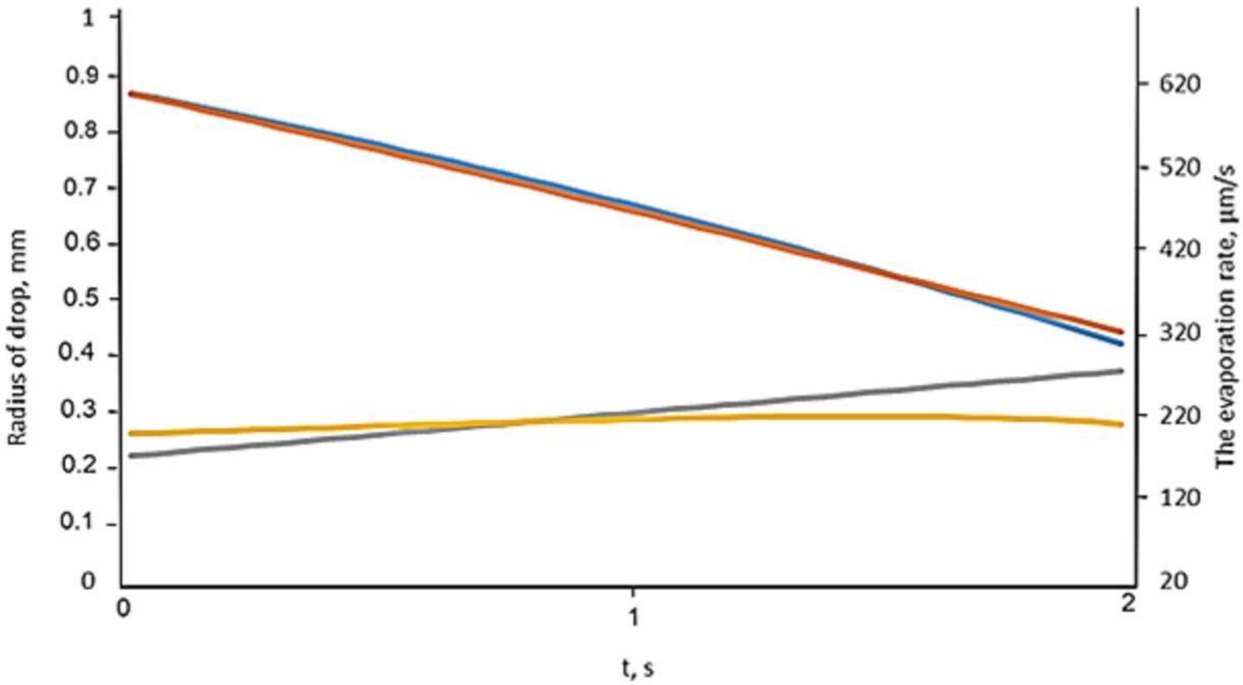

FIGURE 5. Dynamics of the change in the radius of a drop of a 95 % ethanol solution and the modulus of its rate of change versus time at an incoming air flow temperature of 500 °C
droplet radius (experiment- 2degree polinomial), mm; droplet radius (mathematical model), mm;
the evaporation rate (experiment- 2degree polinomial), µm/s; the evaporation rate (mathematical model), µm/s

ANALYSIS OF RESULTS

On figures (Fig. 4) – (Fig. 5) is presented typical results of comparison of the change in radius (and modulus of speed of movement of the droplet radius due to of evaporation), obtained as a result of physical and mathematical modeling.

Based on the results of a comparative analysis of the data obtained during the processing of numerical and mathematical experiments, the following conclusions can be drawn:

1. The time average evaporation rate obtained from the solution of equations (2) – (5) differs by no more than 18% from the results of physical modeling.
2. The greatest differences between the experimental and calculated data are observed when the ratio of the components mass in the solution is approximately equal.
3. Significant differences between the experimental and calculated data are noted in the initial and final periods of evaporation.
4. For a more adequate description of the droplet evaporation processes a two-component solution in a flow, a more complicated model is required.

CONCLUSIONS

A series of experiments was carried out to determine the main parameters of the evaporation of a water-ethanol solution drop in a high-temperature air flow. Based on the experimental results, a simplified mathematical model of the process was formulated, which showed satisfactory agreement with the results of physical modeling and can be recommended for preliminary estimates of the main parameters of the evaporation process.

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REFERENCES

1. A. S. Naumkin and B. V. Borisov, Combust. Explos. Shock Waves **56** (3), 51–56 (2020).
2. V. I. Terekhov, M. V. Gorbachev, and H. Q. Khafaji, Int. J. Heat Mass Transf. **156**, 119821 (2020).
3. A. S. Naumkin, B. V. Borisov, and A. G. Nigay, Matec Web Conf. **194**, 01042 (2018).
4. S.S. Kutateladze, *Basics of heat exchange theory* (Atomizdat, Moscow, 1979) p. 416.
5. K. N. Volkov, V. N. Emelyanov, A. G. Karpenko, and I. V. Teterina, Num. Meth. Prog. **21** (1), 96–114 (2020).
6. Yu.V. Polezhaev and F.B. Yurevich, *Teplovaya zashchita* (Energiya Publ., Moscow, 1976) p. 392.