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## CALCULATION OF EVAPORATION OF A DROP

## РАСЧЕТ ИСПАРЕНИЯ КАПЛИ

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**Abstract**

There are a number of tasks for which it is necessary to solve the problem of evaporation of liquid droplets. This task was solved many times in various ways. However, these solutions use some assumptions: drops are solid inelastic spheres, there is no coagulation, deformation of the drop. Because of this, the quality of the calculation suffers and there may be a difference in the calculations and experimental data. In order to increase the quality of calculations, we have attempted to add corrections to some of the clarifications that correct some flaws.

**Аннотация**

Существует множество задач, для решения которых требуется рассмотреть проблему испарения капель жидкости. Эти задачи решались множество раз различными методами. Тем не менее, эти решения основаны на следующих предположениях: капли имеют жесткую неэластичную форму, не происходит коагуляция, деформация капли. Из-за этого качество решения снижается, и между результатами вычислений и экспериментальными данными возникают расхождения. Для увеличения качества результатов вычислений мы предлагаем добавить поправки к некоторым разъяснениям, которые исправляют некоторые недостатки.

**Introduction**

In this paper, we consider a specific process occurring in the device of an Ejector Contact Heat Exchanger, which is intended for cleaning flue gases and, as a result, improving the condition of the air pools of the territories adjacent to industrial enterprises using the combustion of organic fuels.

The study of the processes occurring during the evaporation of the injected liquid droplets in a contact heat exchanger filter is an important step in obtaining a clear and complete picture that would explain the results obtained in practice. What then can be used to increase the efficiency of this device.

In this paper, the methodology for calculating some processes and the creation of a mathematical model will be considered.

**Objects and research methods**

We will calculate the evaporation of a group of drops.

The approximate amount of liquid needed to cool the gas was obtained in previous calculations. In which, based on the amount of energy in the volume of flue gases, the required amount of an agent capable of absorbing this energy was calculated.

In the calculation we assume that all the necessary liquid is sprayed on droplets of equal size

of a spherical shape that do not collide and do not stick to the walls of our device, and have equal speed. These are the necessary simplifications for the calculation.

Calculation of the gas temperature change

For the calculated amount of a substance, calculations are made according to a compiled mathematical model of droplet evaporation. Take the size distribution of droplets equal. And the same initial velocity drops during injection. The same is assumed to be the same gas saturation with vapor of the substance throughout the volume [1].

Calculation of heat transfer between droplets of sprayed coolant and flue gas. For a system of finely dispersed droplets of a liquid and the gas surrounding them, let us constitute the law of energy conservation, which includes the quantities of gas and liquid, their temperature and state

By how much heat transfer through the walls of the apparatus we ignore, we can accept that the system is closed. We solve the equation for liquid droplets, taking the heat exchange area equal to the contact area of the group of droplets and the gas surrounding them.

Using the law of conservation of energy composed for the system which includes a group of dispersed fine droplets of liquid that evaporate, and the gas to be cooled.

$$E_0 - E = E_B$$

$$m_0 c T_{k0} + (M_0 C_{p_{pa}} + M_v C_{p_v}) * T_{inf0} - m c T_k + ((M_{h0} + m) C_{p_{pa}} + M_v C_{p_v}) * T_{inf0} = m H$$

$$T_{inf} = \frac{m_0 c T_{k0} - m c T_k + (M_0 C_{p_{pa}} + M_v C_{p_v}) * T_{inf0} - m H}{((M_{h0} + m) * C_{p_{pa}} + M_v C_{p_v})}$$

$T_{inf}$ ,  $T_k$  – gas temperature in the vicinity of a drop and at a large distance from it;

$m_n$ ,  $m$ ,  $m_1$  is the mass of the evaporating liquid at the beginning of the process, at the end, and the difference between them,  $c$  is the heat capacity of the liquid,

$C_{pp}$  is the heat capacity of steam,

$C_{pv}$  is the heat capacity of the liquid,

$M_{h0}$  is the mass of saturated steam at  $T_{inf}$ ,

$M_v$  is the mass gas per unit volume.

Having the necessary data using the resulting equation it is possible to obtain the final temperature value. To find out the intermediate values of the calculation made in small steps. The result of the previous calculation becomes the initial data for the subsequent calculation. The calculation is carried out using the fourth order Runge-Kutta method. This is a method of numerical solution of equations, belongs to the class of Euler methods. A feature of the Runge-Kutta method is that it uses several correction factors to clarify the value of each next calculation step, which depends on the number of steps and their “length”.

The driving force of the drop evaporation process is determined by the difference between the partial vapor pressures of the evaporating liquid, away from and above the drop.

$$q_m = \frac{4 * \pi * D_f * M * r * (P_d - P_{h0})}{R * T},$$

$q_m$  is the mass flow;

$D_f$  is the diffusion coefficient;

$M$  is the molecular weight,

$r$  is the drop radius;

$P_d$  is the partial vapor pressure over the drop;

$P_{h0}$  is the partial pressure of saturated vapor;

$R$  is the universal gas constant;

$T$  is the temperature.

Substitute these values into the equation from which we obtain

$$q_m = \frac{4 * \pi * D_f * M * r * \left( 2338.8 * \left( e^{\frac{2 * \sigma * M}{\rho g * R * T_{k0} * r} * \left( \frac{1}{T} - \frac{1}{293} \right)} * e^{-\frac{M * H}{R} * \left( \frac{1}{T_k} - \frac{1}{293} \right)} \right) - 2338.8 * e^{\frac{2 * \sigma * M}{R} * \left( \frac{1}{T} - \frac{1}{293} \right)} \right)}{R * T}$$

The rate of change of the drop radius is calculated as follows. This equation is obtained by

substituting the partial pressure values into the qm equation. And the definition of the mass of a drop of their radius. In order to obtain a change in the radius of a drop in the process of evaporation, we express its radius from the mass of a drop:

$$m_k = \frac{4}{3} \pi r^3 \rho_l$$

$$rv = - \frac{Df * M * r}{2 * \rho g * R * T_{inf}} * (P_d - P_h)$$

The support of the existing definitions in the equation gives the following result

$$rv = - \frac{Df * M * r}{2 * \rho g * R * T_{inf}} * 2338.8 * \left( e^{\frac{2 * \sigma * M}{\rho g * R * T_k * r}} * e^{-\left(\frac{M * H}{R}\right) * \left(\frac{1}{T_k} - \frac{1}{293}\right)} - v * e^{-\frac{M * H}{R} * \left(\frac{1}{T_{inf}} - \frac{1}{293}\right)} \right)$$

rv – the rate of change of the drop radius.

According to Fuchs's work "Evaporation and Growth of Drops in a Gaseous Medium," the rate of evaporation of a drop in a stationary mode is constant. Strictly speaking, this process cannot be stationary, due to the constant change in the drop radius and, consequently, the evaporation rate. But in the case when the concentration of a vapor droplet in the medium, an insignificant process can be considered quasistationary. The formula for calculating the temperature change during heat exchange taking into account the heat exchange and evaporation of the liquid.

### Heat change in the process

Consider two mechanisms for changing heat in the process. Heat transfer between gas and liquid.

As well as the energy carried away by evaporated liquid.

Heat exchange with the environment is determined by the formula [2]

$$q1 = s \lambda / r (T_{inf} - T_k),$$

where s is the area of the heat exchange surface which is in contact with the environment. In our case, this is the surface area of the drop.

$$s = 4\pi r^2.$$

$$q1 = 4\pi r^2 \lambda / r (T_{inf} - T_k).$$

The heat flux during the evaporation of a liquid from the surface of a drop can be expressed as follows.

$$q2 = (cT_k + H) \frac{dm}{dt}.$$

The substance departing from the drop was definitely by us earlier. And we can substitute this value into the equation

$$q2 = -(cT_k + H) - \frac{4\pi Df * r * M}{RT} * (P_d - vP_{h0}).$$

Total heat change:

q1+ q2.

Substitute what we know in the equation after which we get

$$= 4\pi r^2 \frac{\lambda}{r} (T_{inf} - T_k) + \left[ -(cT_k + H) - \frac{4\pi Df * r * M}{RT} * (P_d - vP_{h0}) \right]$$

$\lambda$  – coefficient of thermal conductivity of gas,

v – the amount of evaporating substance in the gas.

The definition is derived from the heat flow equation, which travels from the environment to the drop when the liquid evaporates.

### Research behavior drops

In order to eliminate one of the simplified calculations, namely, the condition that the drops are ideal non-changing spheres, a study was conducted of the available information regarding the process of deformation of the drops in flight.

According to the literature found, the shape of a drop is a complex function of its diameter velocity and such characteristics as density and surface tension. Usually all these parameters are combined in one dimensionless quantity Weber number.

In accordance with the data on flow rates and speeds of droplets in it, we obtained the value of Relative velocity of droplets, and based on this parameter, we calculated the number of Weber for several sections of the device.

For each of them, a calculation was made of changes in the shape and area of droplets. And further on the basis of these data, evaporation of drops was recalculated.

According to the literature, taking into account the true areas of droplets provides a minor clarification of the evaporation process.

Fuchs writes that the refinement averages the speed increase in the evaporation of droplets equal to 2-3%

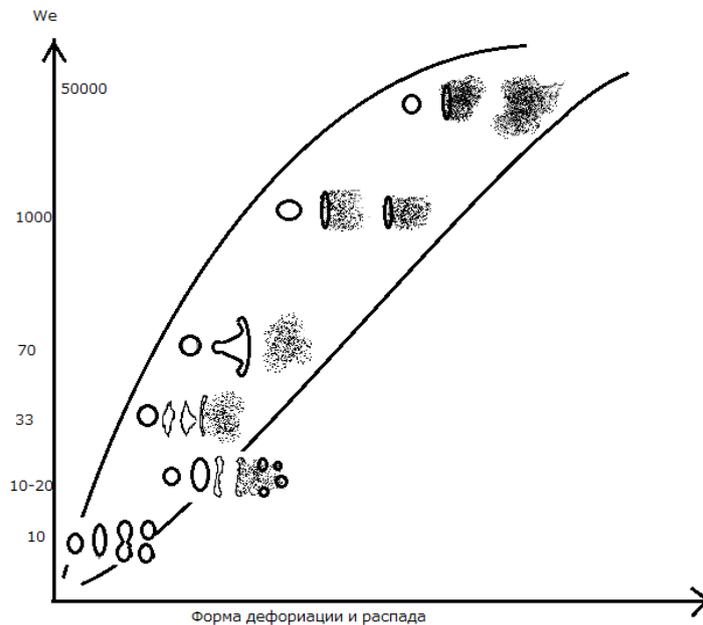


Figure 1 – Drip warp chart

The graph shows how the droplets are deformed and decay as the Weber number increases. At a certain value of this number, the drop during flight passes through certain stages of deformation.

A drop has a critical diameter at which the chances of deformation and further decay are significantly increased. The presence of a critical velocity means that the drop has such a stage at which the deformation is irreversible. When a certain speed is reached, the drop is distorted, but if this speed does not exceed the critical one, then by reducing it, the drop returns to its original forms. When the critical values are reached, small perturbations in the drop can break the drop into several smaller ones.

A drop in flight vibrates due to disturbances arising from the resistance of the oncoming flow and surface tension. If the surface tension of a drop exceeds the force arising when overcoming counter-resistance, the drop remains intact. However, if the surface tension force is significantly less than the drop is deformed and decays.

These values can be shown due to the number of Weber. This number expresses the ratio of active forces of the oncoming flow. And surface tension pressure. The gas pressure at the drop point can be determined as follows.

$$P = \rho u^{2/2}.$$

The surface tension pressure is determined by the Laples formula

$$R_w = 4\sigma / a.$$

$$Pr / Pf \approx We = \rho u^2 a / \sigma.$$

The data obtained for different liquids and the Weber numbers calculated for them are systematized in a table. In which various values and approximate images are entered of how a drop is deformed [3].

For conducting hydrodynamic calculations, there are a number of different methods for calculating turbulent flows. Which differ in accuracy and complexity of calculations, and features of interpretation of the method. Next will be listed some models. After the simplification of the Navier-Stokes equations, in addition to the average velocities, the products of averaged deviations

are added. These deviations are modeled differently.

### Thermal diffusion accounting

In the process of calculations, the results of the rate of change of the drop radius did not coincide with the expected and practical research.

Further work showed the need to account for some of the effects.

The calculations of partial gas pressures were revised. This parameter is incredibly important in the calculation because the pressure difference of vapor of the evaporated substance determines the driving force of the process [4].

Also, at high temperatures or in the case of low-boiling liquids, evaporation becomes not a diffusional character but a thermal diffusional character and, therefore, it is necessary to clarify the diffusion value.

It was planned to take into account the wind coefficient, which determines the effect of the velocity of the drop relative to the gas flow, when the droplet evaporates. But consideration of the processes occurring in our device showed that small drops are carried away by the flow and therefore their speed relative to it is either zero or negligible. Based on this, it was decided to accept that the droplets do not move relative to the gas flow [5].

In view of the above, we obtain a working method for calculating the evaporation of droplets at high temperatures.

### Results and its discussion

Taking into account the deformation of the droplet surface affects the heat transfer of a low-boiling liquid and the lower the boiling point of the liquid, the greater the influence. The transition to the spraying of droplets for ordinary liquids allows to improve the heat transfer and the deformation of the droplets gives a minimal effect. In a low-boiling liquid, the effect of droplet deformation must be taken into account for a mathematical model. Having the ratio of the speed of flow and the movement of particles in them with the rate of evaporation of droplets can be calculated at what point in the filter of the contact heat exchanger all the droplets evaporate. After carrying out these calculations, we can conclude that with the length of the section of 540 mm and while maintaining the speeds, all the droplets will evaporate in the area of 200 mm from the point of injection of the substance.

Having calculated the rate of evaporation of a drop, now using the Runge-Kutta method, we obtain a graph showing the dependence of the drop radius over time.

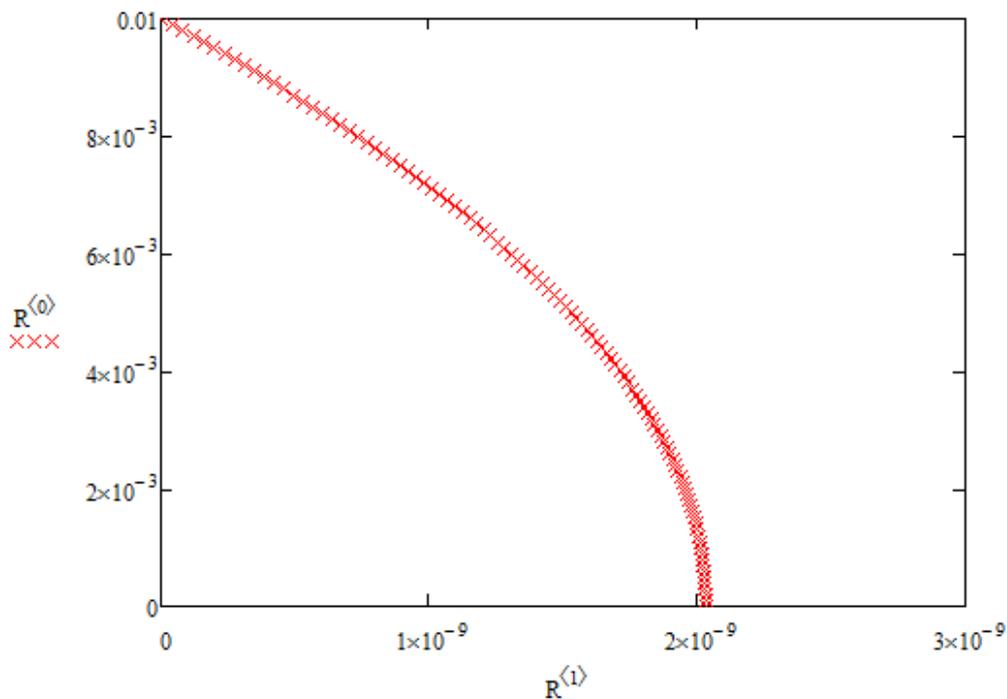


Figure 2 – Evaporation droplet graph

The graph shows that the drop evaporates in a short time  $2.031 \cdot 10^{-9}$  seconds. This can be explained by the low boiling point of the agent and the high temperature of the gas. (The large difference between the boiling point of the agent and the gas temperature) By the end of the evaporation process, the rate increases dramatically, which can be explained by a decrease in the drop radius.

When the boiler reaches a certain temperature, these resins break down into relatively harmless components. Accordingly, it is not entirely correct to calculate the gas cooling for one temperature. We choose several averaged temperature values in those areas of the boiler installation where carcinogenic resins are released. These points are 493 K (220°C), 593 K (320°C), 693 K (420°C). Accordingly, for each point, the calculations described above are carried out. The results of calculations of each of the areas are plotted.

The overall dynamics of the process is preserved in those areas for which the calculation was carried out.

The same graph is constructed for the time of evaporation of the droplets at different initial gas temperatures. For a higher initial temperature, the time required for evaporation is increased. This is because more liquid is needed to cool a hotter gas.

### Findings

A method and a model were created using which it is possible to obtain data on thermal processes during the evaporation of small droplets in a moving stream. According to her first results obtained. Further it is planned to check these data experimentally.

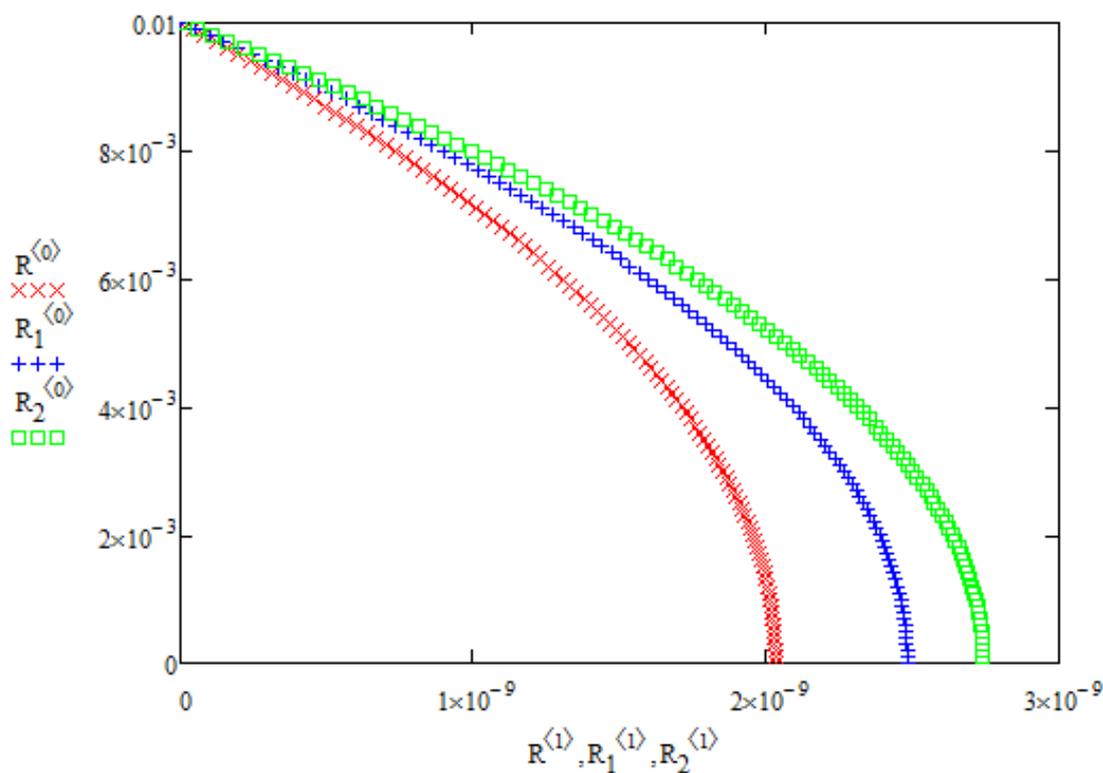


Figure 3 – And the change in the radius of the droplets for the three initial temperatures  
 493 K (220°C)  $2.031 \cdot 10^{-9}$  seconds  
 593 K (320°C)  $2.482 \cdot 10^{-9}$  seconds  
 693 K (420°C)  $2.741 \cdot 10^{-9}$  seconds

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