Artículo de investigación

Effect of phase changes on the effectiveness of cooling by emulsions

Efecto de los cambios de fase sobre la efectividad del enfriamiento por emulsiones
Efeito de mudanças de fase na eficácia de esfriamento por emulsões

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Abstract

The paper considers the effect of the low-boiling dispersed phase on the nature of heat transfer in systems of immiscible liquids. In particular, the behavior of droplets of the dispersed phase during bubble boiling in the volume of an underheated continuous emulsion medium has been studied. Phase transformations predetermine the complex nature of the joint behavior of hydrodynamic and thermal processes. During cooling, the thermal energy is converted into mechanical energy of the vaporized motion of the evaporating liquid disturbed by vapor bubbles. This leads to a change in the volume and size of the droplets of the dispersed phase. It is known that controlled dispersion conditions with a minimum amount of cooling lubricant (emulsion concentration) can improve the quality of metal processing by 10-18%. The dependence obtained by Labuntsov for boiling a homogeneous liquid was used as a characteristic for the rate of thermal motion. The modification of the Labuntsov model is made on the basis of the nature of the physical processes occurring during boiling inside the emulsion droplets at the interface. Based on the analysis of the experimental data of Bulanov, features of heat transfer in the emulsion during bubble boiling of dispersed drops of a low boiling liquid were revealed. The heterogeneity of heat transfer is noted; it is associated with the formation of a kind of steam shroud of boiled droplets near a heated surface, which blocks the

Resumen

El documento considera el efecto de la fase dispersa de bajo punto de ebullición sobre la naturaleza de la transferencia de calor en sistemas de líquidos inmiscibles. En particular, se ha estudiado el comportamiento de las gotitas de la fase dispersa durante la ebullición de burbujas en el volumen de un medio de emulsión continuo sobrecalentado. Las transformaciones de fase predeterminan la naturaleza compleja del comportamiento conjunto de los procesos hidrodinámicos y térmicos. Durante el enfriamiento, la energía térmica se convierte en energía mecánica del movimiento vaporizado del líquido de evaporación perturbado por burbujas de vapor. Esto conduce a un cambio en el volumen y el tamaño de las gotitas de la fase dispersa. Se sabe que las condiciones de dispersión controladas con una cantidad mínima de lubricante refrigerante (concentración de emulsión) pueden mejorar la calidad del procesamiento del metal en un 10-18%. La dependencia obtenida por Labuntsov para hervir un líquido homogéneo se usó como una característica para la tasa de movimiento térmico. La modificación del modelo de Labuntsov se realiza sobre la base de la naturaleza de los procesos físicos que ocurren durante la ebullición dentro de las gotas de emulsión en la interfaz. Sobre la base del análisis de los datos experimentales de Bulanov, se revelaron las características de la transferencia de calor en la emulsión durante la ebullición de

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heat flow. A good agreement with experimental data confirms the adequacy of the model concepts of boiling drops in liquid emulsions.

Keywords: emulsion, heat transfer, boiling, phase transformations, vapor bubbles, cooling.

burbujas de gotas dispersas de un líquido de bajo punto de ebullición. Se nota la heterogeneidad de la transferencia de calor; se asocia con la formación de una especie de cubierta de vapor de gotitas hervidas cerca de una superficie caliente, que bloquea el flujo de calor. Un buen acuerdo con los datos experimentales confirma la idoneidad de los conceptos modelo de gotas de ebullición en emulsiones líquidas.

Palabras claves: Emulsión, transferencia de calor, ebullición, transformaciones de fase, burbujas de vapor, enfriamiento.

Resumo

O artigo considera o efeito da fase dispersa de baixo ponto de ebulição na natureza da transferência de calor em sistemas de líquidos imiscíveis. Em particular, foi estudado o comportamento de gotículas da fase dispersa durante a ebulição de bolhas no volume de um meio de emulsão contínuo sobreaquecido. Transformações de fase predeterminam a natureza complexa do comportamento conjunto de processos hidrodinâmicos e térmicos. Durante o resfriamento, a energia térmica é convertida em energia mecânica do movimento vaporizado do líquido de evaporação perturbado por bolhas de vapor. Isto leva a uma mudança no volume e tamanho das gotículas da fase dispersa. Sabe-se que as condições de dispersão controlada com uma quantidade mínima de lubrificante de arrefecimento (concentração de emulsão) podem melhorar a qualidade do processamento de metal em 10-18%. A dependência obtida por Labuntsov para ferver um líquido homogêneo foi usada como uma característica para a taxa de movimento térmico. A modificação do modelo de Labuntsov é feita com base na natureza dos processos físicos que ocorrem durante a fervura no interior das gotículas de emulsão na interface. Baseado na análise dos dados experimentais de Bulanov, as característica da transferência de calor na emulsão durante a ebulição de bolha de baixas dispersas de um líquido de baixo ponto de ebulição revelaram-se. A heterogeneidade da transferência de calor é notada; está associado à formação de uma espécie de cobertura de vapor de gotículas fervidas perto de uma superfície aquecida, que bloqueia o fluxo de calor. Um bom acordo com dados experimentais confirma a adequação dos conceitos do modelo de gotas em ebulição em emulsões líquidas.

Palavras-chave: Emulsão, transferência de calor, ebulição, transformações de fase, bolhas de vapor, resfriamento.

Introduction

The effectiveness of any coolant is determined by the density of the heat flow withdrawn by them in a fairly wide range of temperatures. Heat capacity coolant plays a decisive role at a moderate temperature not exceeding the temperature of its saturated vapor. With a further increase in temperature, conditions are created for phase transformations; vapor phase bubbles are formed which increase the heat flow in accordance with the latent heat of vaporization fluid. This important reserve of cooling capacity is limited only by the onset of a boiling crisis associated with the formation of a vapor phase layer with a low heat capacity at the heated surface. It turned out that they can control and optimize the cooling efficiency due to other thermophysical factors in contrast to the heat capacity.

The works of N. V. Bulanov and B.M. Hasanov show the advantages of using emulsions of immiscible liquids as heat carriers compared to homogeneous liquids and solutions. For this purpose, the physical mechanisms of the features of boiling emulsions, in particular, the dependence of boiling intensity of the heat carrier on the number of nucleation centers is considered in detail. As their number increases, the heat flux and heat transfer coefficient also increase. However, unlike a homogeneous liquid, when an emulsion boils with a low-boiling dispersed phase, the heating surface contacts with a high-boiling continuous medium, the saturated vapor temperature of which is higher than the surface temperature. Therefore, for the formation of nucleation centers on the heating surface itself, there are no conditions for the boiling process. The boiling of droplets of the dispersed phase occurs not on the heated surface itself, but in the thermal boundary layer of the continuous medium. The droplets of the dispersed phase can be heated there to a temperature above the temperature of their saturated vapors. For boiling it is necessary that at least one nucleation center should be activated (Bulanov, 2001; Hasanov & Bulanov, 2014).

Experimental studies have established the characteristic features of the boiling process, which determine the efficiency of heat exchange in emulsions. The main of them are the wide temperature range of formation of vapor bubbles in low-boiling droplets and significant overheating necessary for the start of intensive boiling (Bulanov & Gasanov, 2008). The emulsion boils only at the temperature of the heat-transfer surface TW, which significantly exceeds the temperature of the saturated vapor T S of the dispersed phase. The observed delay in the onset of boiling reaches 100 °C and persists throughout the observation time (Hasanov & Bulanov, 2010). However, this phenomenon, being undesirable for the boiling process, is another factor for increasing the heat flux density in coolants. It is associated with the size of droplets of the dispersed phase.

An important area of application of cooling emulsions is metal cutting, grinding, polishing, as well as reducing tool wear. Oil is the main active agent in the MQL (minimum quantity lubrication) method. Its main task is only to lubricate the treated surface. In the method MQCL (minimum amount of cooling lubrication) the main tool is a concentrated emulsion. In this method, the main task along with lubrication is cooling the cutting zone. To do this, it is necessary to create such emulsions that are able to ensure the removal of the maximum possible amount of heat (Maruda et al, 2017a; Maruda et al, 2017b).

To reduce the temperature during the processing of metals in the cutting zone, lubricating and cooling emulsions are usually used. However, most refrigerants used in mechanical processing contain harsh chemicals and are not biodegradable. Therefore, the negative impact on the environment and high disposal costs limit the volume of cooling emulsions. To do this, there should be selected such parameters of the emulsion as the concentration and size of the dispersed phase droplets, which are able to support the necessary cooling modes (Hasanov & Bulanov, 2014; Maruda et al, 2016).

Methods

The general solution of applied problems in analytical form obtained with the help of a mathematical model of a physical phenomenon represents all possible particular solutions for any initial and boundary conditions. If, in the presence of a mathematical model, there is no explicit solution to the problem, it is necessary to use specialized software, the basis of which is theoretically sound algorithms. But the question of the adequacy of computer models for complex physical phenomena requires a preliminary justification which often is not less complex.

When a software algorithm uses a common method of finding solutions to a mathematical problem, it guarantees the result: the necessary particular solution. So for solving problems of heat and mass transfer in homogeneous liquids, numerical methods of continuous fluid hydrodynamics (CFD) are widely used using software like Code_Saturne or PHOENICS. However, most engineering tasks of practical interest are related to the use of multi-phase and multi-component working media. There are no sufficiently general model representations for them of the joint motion and interaction between liquids and gases under conditions that represent a controlled technological process. Here there is a more difficult task - to obtain the corresponding specific solution. For this, it is necessary to modify the general mathematical model supplementing it with the results of preliminary experimental studies and a priori physical concepts.

An even more complex physical process is the boiling of heterogeneous liquid emulsions, in which the characteristics of mass, momentum and energy transfer depend not only on heat exchange conditions, but also on physicochemical properties, volume concentration and size of droplets in the dispersed phase. The mutual influence of transfer processes in heterogeneous systems complicates the description of thermodynamic boiling regimes due to the large number of mechanisms of elementary physical phenomena that are part of them. This is the main problem associated with the model ideas that arise when performing analytical, numerical and experimental studies of heat transfer in emulsions.

- Modification of the liquid emulsions boiling model with a low-boiling dispersed phase. Boiling in emulsions with a low-boiling dispersed phase requires much more thermal energy compared to removing heat from a homogeneous coolant. The phase transformations of dispersed droplets supplement it with the heat consumed for vaporization. But at the same time, the interfacial surface with a high-boiling continuous medium which mediates the contact of the droplets with the cooled surface, serves as the heating surface for the droplets of the dispersed phase. This contributes to the localization of vapor in the volume of emulsion droplets, which prevents the onset of a boiling crisis under normal conditions and leads to an increase in the efficiency of heat exchange. However, to date there is no complete clarity regarding the physical ideas about the mechanisms of boiling in the volume of droplets of the dispersed phase limited by the interfacial surface. It is a complex, rapid, and physical process that is not amenable to analytical description or direct experimental measurements.

Only phenomenological models modified on the basis of their experimental studies can serve as a method for studying such physical phenomena. Then it is necessary to justify their acceptability using the available indirect data for estimating empirical constants. The Labuntsov's model was adopted as the basis for the cooling emulsion model which describes the bubble-boiling regime of a homogeneous liquid on a solid heating surface (Labuntsov, 2000). He developed a semi-empirical theory of bubble boiling, according to which the heat flux density q which is removed from the heated surface to the homogeneous fluid boiling on it, consists of two components:

$$q = q_1 + q_2 \, . \tag{1}$$

The first component q l is determined by the thermal conductivity of the liquid λ through a viscous sublayer at the cooled surface with thickness δ:

$$q_1 \sim \lambda \frac{\Delta T}{\delta} \, . \tag{2}$$

Labuntsov has proposed to calculate the value of δ by analogy with near-wall turbulence characterized by the average pulsation velocity of the "thermal" motion. $\bar{u}$:

$$\delta \sim \frac{\nu}{\bar{u}} \, , \tag{3}$$

Where ν is the kinematic viscosity of the fluid.

Magnitude $\bar{u}$ is due to the transformation of the heat flux which moves from the solid wall and is spent on the formation of vapor bubbles, into the pulsating motion of the surrounding liquid. It is determined by the energy balance between the mechanical energy of a pulsating motion $\rho_l \bar{u}^2$ and thermal energy spent on the formation and growth of vapor bubbles:

$$\rho_l \left(\frac{dR}{dt} \right)^2 R^2 n_s^* \sim \rho_l \bar{u}^2 \, , \tag{4}$$

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where R is the current radius of the vapor bubble, n_s^* - the number of active boiling centers on the heating surface.

The second component q 2 is determined by the cost of heat for the evaporation of a part of the liquid that has passed into the vapor state:

$$q_2 = r\rho_v \bar{u} \quad (5)$$

The modification of the Labuntsov model was made on the basis of the identity of the physical processes occurring during the boiling of a homogeneous liquid on the heating surface with boiling inside the emulsion droplets at the interface. Parameter n_S^* in the Labuntsov's model (the number of active boiling centers per unit of heating surface) is replaced in the emulsion by $n_{sэ}^*$ (the number of boiling drops of a thin superheated layer per unit of heating surface). As a result, in the relation (4) more general parameter $n_{sэ}^*$ is used instead of the parameter n_S^*, which is determined taking into account the effects of pulsations of a continuous medium (Rozentsvaig & Strashinsky, 2011):

$$n_{sэ}^* = n_{sэ}\left(\frac{\rho_c \bar{w}^2 R_0^3}{W_0}\right)^{\beta} \quad (6)$$

where W 0 is the total excess energy for formation of a critical vapor nucleus (Skripov, 1972), n se is the number of droplets in a thin superheated layer of the emulsion per surface unit, ρ s - density of the continuous medium, $\bar{w}$ is the root-mean-square velocity of the fluctuations of the continuous medium of the emulsion, R 0 is the initial radius of a homogeneous drop. The exponent value β is found by matching the final dependence with a priori generally accepted ideas about the important characteristics of the nucleation processes under the influence of external pulsations.

The magnitude of the surface concentration n se is determined by the generalization of the calculated concentration of drops n in the original emulsion as $n_{sэ} \sim \sqrt[3]{n^2}$. The equation (6) thus converted will take the form

$$n_{sэ}^* \sim \sqrt[3]{n^2}\left(\frac{\rho_c \bar{w}^2 R_0^3}{W_0}\right)^{\beta} . \quad (7)$$

This relation modifies equation (4) for the boiling conditions of the dispersed phase droplets as follows:

$$\rho_c\left(\frac{dR}{dt}\right)^2 R^2 \sqrt[3]{n^2}\left(\frac{\rho_c \bar{w}^2 R_0^3}{W_0}\right)^{\beta} \sim \rho_c \bar{u}^2 \quad (8)$$

The formation and growth of a vapor bubble in a drop located in a superheated layer of a high-boiling continuous medium near the heating surface are assumed to be in many ways similar to the formation and growth of a vapor bubble in a homogeneous liquid on the heating surface:

$$R \sim \sqrt{\frac{\lambda_c \Delta T}{r \rho_v}} \sqrt{t}, \qquad (9)$$

where r is the specific heat of vaporization, ρ_v - steam density.

To determine $\bar{u}$, let's use equations (8), (9)

$$\bar{u} \sim \frac{\lambda_c}{r\rho_v} \sqrt[3]{n} \left(\frac{\rho_c \bar{w}^2 R_0^3}{W_0} \right)^{\frac{\beta}{2}} \Delta T. \qquad (10)$$

In this case, the density of the heat flux withdrawn from the heated surface will be determined as

$$q = \frac{\lambda_c}{r\rho_v} \sqrt[3]{n} \left(\frac{\rho_c \bar{w}^2 R_0^3}{W_0} \right)^{\frac{\beta}{2}} \left(C_2 \frac{\lambda_c}{\nu_c} \Delta T^2 + C_1 r \rho_v \Delta T \right), \qquad (11)$$

where C 1 and C 2 are empirical constants determined in the course of experiments.

- The nature of heat transfer when cooling of a solid heating surface by the emulsion. To compare the theoretical model (11) with the experimental data, it is necessary to transform the formula for the number of boiled emulsions drops n s per unit of one-dimensional surface of the heated wire. The number of superheated droplets in the superheated layer of wire under heating with length of l corresponds to $n_l \sim \sqrt[3]{nl}$. Then the number of drops per unit surface of the heated wire will correspond to $n_s \sim \frac{\sqrt[3]{nl}}{dl} = \frac{\sqrt[3]{n}}{d}$, and the number of boiled drops near the surface with a unit area will be equal to $n_{sэ}^{*} \sim \frac{\sqrt[3]{n}}{d}$.

Taking into account the change in the relationship between the countable n and the volume concentration of droplets of the dispersed phase C, equation (11) with β = 0 takes the following form:

$$q = \frac{\lambda_c}{r\rho_v} \frac{\sqrt[6]{C}}{\sqrt{R_0 d}} \left(C_2 \frac{\lambda_c}{\nu_c} \Delta T^2 + C_1 r \rho_v \Delta T \right). \qquad (12)$$

Figure 1 presents the calculated curves (Rozentsvaig, 2014) for the emulsion: water-silicone liquid PES-5 at various volume concentrations. The dots mark the experimental data presented in (Bulanov, 2006).

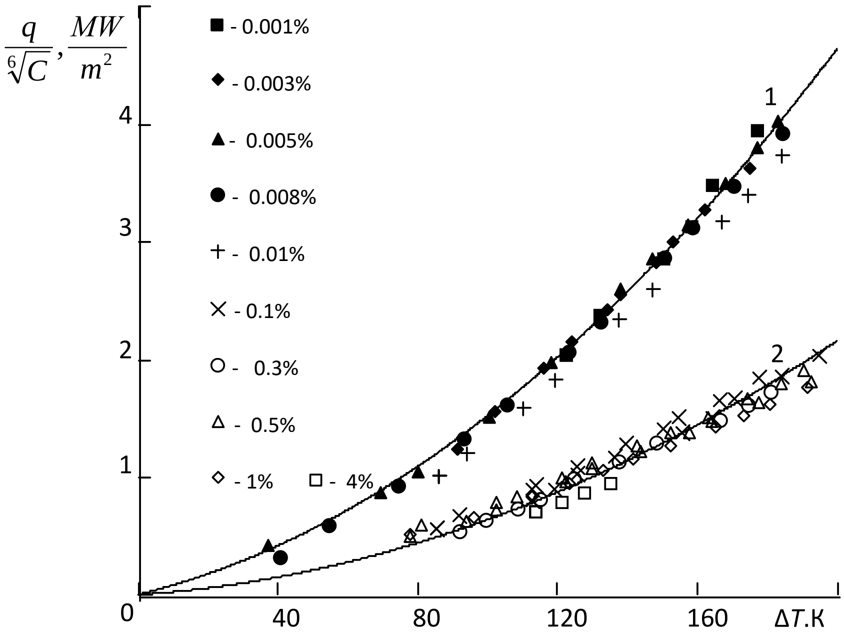

Fig. 1. Heat flow from overheating emulsion: water - silicone fluid PES-5.

It can be noted that the experimental data were divided into two separate groups, approximated by different model curves. Moreover, curve 1 correlated well with volume concentrations of 0.001 - 0.01%, and curve 2 - with concentrations of 0.10% and more. This result indicates the non-uniform nature of heat transfer in emulsions with a low-boiling dispersed phase. It is caused by the fact that vaporization occurs not on the heating surface, as during the boiling of a homogeneous liquid, but at some distance from it. At a certain content of the vapor phase, the droplets can behave like a vapor film and block the flow of heat to the more distant droplets. For the formation of a steam blanket, it is necessary that the bubbles, with complete evaporation of the dispersed droplets of the low-temperature liquid, can contact each other. The limiting value of the concentration of droplets is determined from the ratio of the densities of the liquid and vapor phases C max = r v / r l = 0.06%. This corresponds to the boundary of the separation between boiling regimes presented in Fig. 1.

Results and Discussion

The obtained ratios for the heat flux density during boiling of the low-boiling dispersed phase of cooling emulsions are qualitatively confirmed by experimental data (Vieira, 2001). They note that emulsions not only improve heat removal, but also reduce heat due to friction. The combination of these properties determines the effectiveness of each coolant for machining metals.

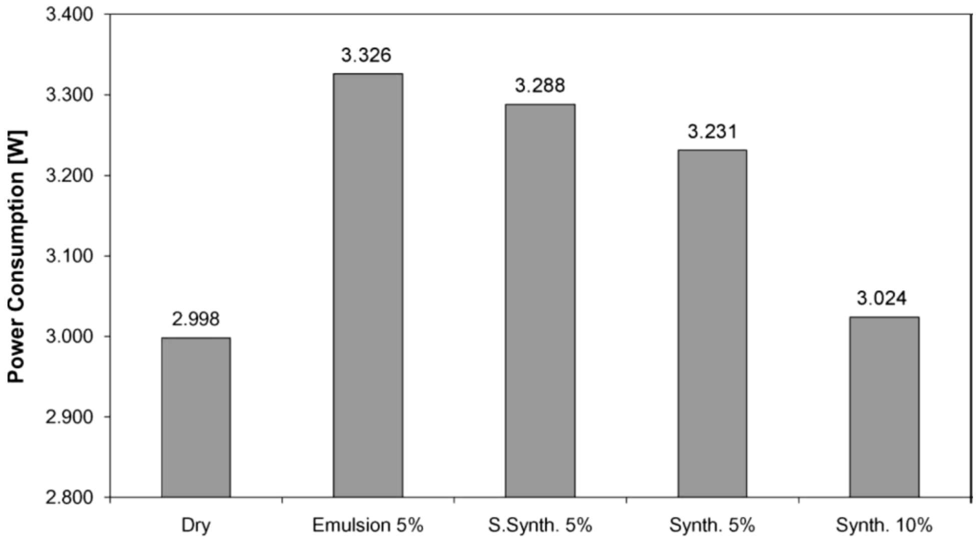

Fig. 2. Powder consumption recorded during the first pass (Vieira, 2001).

Figure 2 shows the results of tests of the heat energy withdrawn with the use of various technologies. It shows that processing without cutting fluid has withdrawn the least energy. It is followed by a synthetic liquid with a concentration of 10 and 5%, and a semi-synthetic liquid. The emulsion-based fluid shows the maximum heat flow that is removed from the surface to be treated.

Important features of the practical application of emulsions were noted in the field of metal processing technology using the minimum quantity cooling lubricant method (Maruda et al, 2017a; Maruda et al, 2017b). In particular, it was found that the size of the droplets is an important factor in the processing when using this method. Proper maintenance of the dispersed composition can provide a significant increase in the cutting performance of the tool and reduce the wear rate of the cutting tool. Controlled conditions for dispersing emulsions with minimal cooling lubricant can improve the quality of metal processing by 10–18% under cooling conditions in accordance with the data of (Maruda et al, 2017b).

Phase transformations not only significantly change the state of the emulsion, but also affect the hydrodynamic characteristics of vapor-liquid systems (Rozentsvaig & Strashinskii, 2014). In this case, thermal energy is converted into mechanical energy of motion of an evaporating liquid, perturbed by the growth of vapor bubbles. Therefore, the detail description of physical and model ideas about the effect of size and concentration of droplets on the processes of heat and mass transfer in liquid emulsions remains an urgent task.

Summary

The behavior features of the superheated droplets of the dispersed phase with phase transformations in the volume of a cooling emulsion are considered. A generalized criterial model for calculating the density of the heat flux removed by the emulsion from the heated surface is proposed.

The heat transfer features in the emulsion with bubble boiling of dispersed drops of low-boiling liquid are revealed. The heterogeneity of heat transfer is noted; it is associated with the formation of a kind of vapor sheet of boiled droplets near a heated surface that blocks the heat flow.

The necessity of taking into account the size of droplets on the formation of nuclei and the growth of vapor bubbles which increase the heat capacity of the cooling emulsion is shown.

Conclusions

The influence of the phase transformations of the low-boiling dispersed phase on the nature of heat exchange in liquid emulsions is accompanied by new mechanisms of thermodynamic phenomena. The interrelated behavior of hydrodynamic and thermal processes in vapor-liquid systems is due to the formation of nuclei and the growth of vapor bubbles. They complicate the picture of bubble boiling in droplets dispersed in the volume of the underheated continuous medium of the emulsion. But, on the other hand, many engineering tasks of practical interest are associated with the use of multi-phase and multi-component working environments.

Expansion of the range of elementary physical phenomena mechanisms improves model representations regarding the boiling of droplets in liquid emulsions with phase changes. They allow detailing the relationship of hydrodynamic and thermal processes when performing thermophysical calculations. In turn, this contributes to increase the efficiency of technological processes in which cooling emulsions are used.

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