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Mathematical modeling of separation process by coupled heat transfer in the inertial-filtering gas separator-condenser

Introduction

Analysis of the high-dispersed drop fluid formation in the turbulent two-phase flows is a very current task important for transporting natural gas through the pipelines and for its purification in the technological equipment. Drops in the gas flow can be formed without condensation process (coagulation or breakup) or when condensation takes place (usually when using special devices which change thermodynamical parameters of the system – the devices for prior condensation DPC [*Liaposhchenko et al., 2013; Liaposhchenko and Nastenko, 2013*].

A new method of such separation systems was proposed after an analysis of physical conditions of high-dispersed drop fluid formation in the natural gas flow. Inertial filtering separation using condensation process [*Sklabinskyy, et al., 2014*] is based on the compulsory change of thermodynamic parameters of the gas-fluid mixture which enters separation channels of the inertial filtering separator [*Sklabinskyy and Liaposhchenko, 2004*], and so phase equilibrium in the pipeline is upset.

The advantages of the method proposed are as follows:

- materials consumption of the refining equipment is less because one doesn't need additional devices for prior condensation,
- the device construction is very easy,
- gas fluid systems separation is effective and water vapor content is high,
- the device can withdraw coarse fraction of hydrocarbons from the gas (gasoline extraction from gas),
- it can operate by high liquid load.

Cold agent (hydrocarbon condensate) is supplied to the curvilinear drainage channels, closed for the gas flow, and it creates the conditions for simultaneous separation and condensation processes which in its turn causes water steam condensation and also coagulation of fine drops in the gas-fluid flow entering the separation channels (Fig. 1). Such method of gas-fluid systems separation can be used as an alternative to the devices for prior condensation.

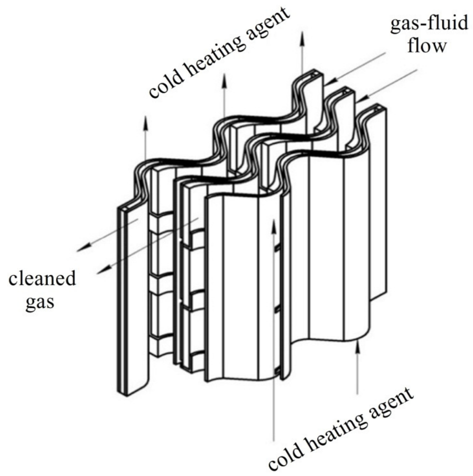

Fig. 1 Scheme of the flows moving during the inertial filtering process by condensation [*Sklabinskyy et al., 2014*]

Theoretical basis and mathematical modeling

Study on the separation process by coupled heat transfer in the inertial-filtering separator-condenser using mathematical modeling of these processes has been pursued. When inertial-filtering separation process takes place and thermodynamic parameters of the gas-fluid system are changed (it means that gas dispersed mixture moves near colder wall) two separate processes take place in the gas flow: steam condensation and heat transfer. The main view is then to determine condensed fluid phase amount.

As it was found out in [*Liaposhchenko et al., 2013; Liaposchenko and Nastenko, 2013*], fluid phase formation by condensation of heavy hydrocarbons steam starts when steam reaches the supersaturation level higher than the critical one, so when the saturation $s > s_{cr}$. To get the formula for determining the supersaturation level for inertial filtering separation using condensation method one can use the usual equations for heat and mass transfer [*Amelin, 1951*]:

$$dG_S = \beta_p F(p - p_2)dt \tag{1}$$

$$dQ = \alpha F(T - T_2)dt \tag{2}$$

where:

G_S – the amount of substance, which comes from the gas phase into the liquid one, [kg·s^{-1}]
β_p – the coefficient of mass transfer from gas flow to the surface of phase contact at steam condensation, [kg·m^{-2}s^{-1}]
F – condensation surface, [m^2]
p – steam pressure in the gas mixture, [Pa]
p_2 – steam pressure near the condensation surface, [Pa]
t – time, [s]
Q – separator-condenser heat load, [J]
α – heat transfer coefficient, [W·m^{-2}K^{-1}]
T – gas mixture temperature, [K]
T_2 – condensation surface temperature, [K]

Thus the amount of substance transferred from the gas phase into the liquid one is:

$$G_S = \frac{GM_S p}{MP} \tag{3}$$

where:

G – gas mixture mass, [kg]
M_S – steam-like substance molecular mass, [kg·kmol^{-1}]
M – gas mixture average molecular mass, [kg·kmol^{-1}]
P – total pressure, [Pa].

Eq. (3) can be written in the forms of:

$$\frac{G}{M} = \frac{G_N p}{M_N(P - p)} \tag{4}$$

and

$$G_S = \frac{G_N M_S p}{M_N(P - p)} \tag{5}$$

where:

G_N – the amount of gas, which is not condensed, [kg]
M_N – molecular mass of the gas, which is not condensed, [kg·kmol^{-1}].

After differentiation of the Eq. (5), one gets the formula as follows:

$$dG_S = \frac{G_N M_S P dp}{M_N (P-p)^2} \tag{6}$$

Amount of the transferred heat can be expressed by the equation:

$$dQ = GcdT = \frac{G_N PMc}{M_N (P-p)} dT \tag{7}$$

where:
c – specific heat of the gas mixture [$J \cdot kg^{-1} K^{-1}$]

Thus, considering the equations, one can write:

$$\frac{dp}{dT} = \frac{Mc(P-p)}{M_S} \frac{\beta_p}{\alpha} \frac{p-p_2}{T-T_2} \tag{8}$$

Let us call:

$$\delta = \frac{Mc(P-p)}{M_S} \frac{\beta_p}{\alpha} \tag{9}$$

then

$$\frac{dp}{dT} = \delta \frac{p-p_2}{T-T_2} \tag{10}$$

When inertial-filtering separation process takes place by condensation one can consider the coolant fluid temperature as a fixed one, taking into account that the condensation temperature is constant and so steam pressure near the condensation surface is also constant.

After integrating Eq. (10) in the range from p_1 to p and from T_1 to T one can determine the steam pressure in the gas mixture as follows:

$$p = \left(\frac{T-T_2}{T_1-T_2}\right)^{\delta} (p_1 - p_2) + p_2 \tag{11}$$

Taking into consideration that the supersaturation is the ratio of steam pressure in the gas to the pressure of saturated steam, and dividing the Eq. (11) on the saturated steam pressure (gas temperature T) one gets the following formula for determining the supersaturation:

$$S = \left(\frac{T-T_2}{T_1-T_2}\right)^{\delta} \frac{p_1-p_2}{p_{SS}} + \frac{p_2}{p_{SS}} \tag{12}$$

where:
S – steam supersaturation at the end of the process
T_1 – temperature of the gas at the beginning of the process, [K]
p_1 – steam pressure in the gas at the beginning of the process, [Pa]
p_{SS} – saturated steam pressure, [Pa]

As can be seen from the Eq. (12), the functional dependence $S = f(T)$ has a maximum [*Amelin, 1951*]. It means that there is a temperature at which the supersaturation occurring during condensation on the surface reaches a maximal value.

When substituting p_{SS} in the Eq. 12) one obtains as follows [*Amelin, 1951*]:

$$\frac{\partial T^2}{E(T-T_2)} - \frac{p_2}{p_1-p_2}\left(\frac{T_1-T_2}{T-T_2}\right)^{\delta} - 1 = 0 \tag{13}$$

where:
T – temperature of the gas mixture in the zone of maximum supersaturation [K]

Mass concentration of vapor formed by condensation of steam on the surface is defined by the equation:

$$G_{f.f.} = \frac{Mp_{SS}}{RT}(S-1) \tag{14}$$

If one substitutes the supersaturation equation to this formula (12) one obtains [*Amelin, 1951*]:

$$G_{f.f.} = \frac{M}{RT}\left[\left(\frac{T-T_2}{T_1-T_2}\right)^{\delta}(p_1-p_2) + p_2 - p_{SS}\right] \tag{15}$$

When condensation process takes place on the surface of the separation channel walls, supersaturation is significantly reduced what results in heat emission by condensation. Thus walls surface temperature is rising and becomes higher than the gas mixture temperature. Therefore, it is necessary to remove heat from the surface of the channel wall, which would allow further condensation of steam on it.

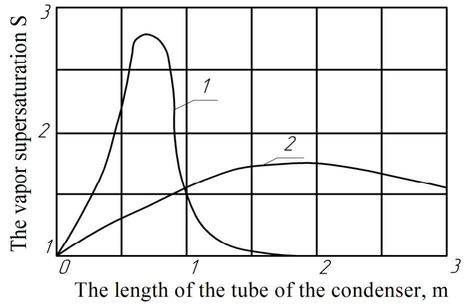

Fig. 2. Supersaturation along the length of the condenser pipes at various temperatures cooling water: 1 – 293 K, 2 – 313 K

In the monograph [*Amelin, 1951*] there was proposed the method of calculation for water vapor condensation from the air in a tubular condenser. The results of calculations are presented in Fig. 2. The vapor supersaturation at first increases, reaches a maximum and then decreases. Thus, the lower temperature of cold agent and the higher the maximum supersaturation of the vapor can be determined.

Conclusions

Inertial filtering separation method using condensation which is presented in the article is a new and alternative one to the traditionally used methods of prior condensation for gas-condensate systems depuration.

Using the worked out separation model of coupled heat transfer in such inertial-filtering gas separator-condenser one can determine fluid phase amount which is condensed in the process and also the main parameters of heat and mass transfer.

Further research is directed to the study of heat and mass transfer efficiency in the inertial-filtering gas separator-condenser by different operating modes using mathematical and computer modeling methods and experimental research. Engineering calculating method of such equipment will be worked out on the basis of received results.

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