Study on Gas-liquid Falling Film Flow in Internal Heat Integrated Distillation Column

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Abstract: Gas-liquid internally heat integrated distillation column falling film flow with nonlinear characteristics, study on gas liquid falling film flow regulation control law, can reduce emissions of the distillation column, and it can improve the quality of products. According to the distribution of gas-liquid mass balance internally heat integrated distillation column independent region, distribution model of heat transfer coefficient of building internal heat integrated distillation tower is obtained liquid distillation falling film flow in the saturated vapour pressure of liquid water balance, using heat transfer equation and energy equation to balance the relationship between the circulating iterative gas-liquid falling film flow area, flow parameter information, at a given temperature, pressure conditions, gas-liquid flow falling film theory makes the optimal parameters to achieve the best fitting value with the measured values. The results show that the geometric gas-liquid internally heat integrated distillation column falling film flow heat exchange area and import column thermostat, the average temperature has significant. The positive correlation between the heat exchanger tube entrance due to temperature difference between inside and outside, the heat flux is larger, with the increase of internal heat integrated distillation column temperature, the slope decreases its temperature rise, which accurately describes the internal gas-liquid heat integrated distillation tower falling film flow regularity, take appropriate measures to promote the enhancement of heat transfer. It can enhance the overall efficiency of the heat exchanger.

Keywords: internal heat integrated distillation column; gas-liquid falling film flow; liquid water balance; heat transfer efficiency.

1. Introductions
Distillation is a distillation tower vapor-liquid contact devices, there are two main types of plate column and packed column, according to the mode of operation can be divided into continuous distillation and batch distillation. The internally heat integrated distillation column consists of evaporator, condenser and several parts thermostat, the internally heat integrated distillation column steam enters from the bottom of the column, the gas and the evaporated liquid drop of countercurrent contact phase contact, the drop in the volatileness(low boiling) components to gas phase transfer, difficult volatile gas phase (high boiling point) component continued to decline in liquid medium transfer, gas phase is close to the top of the tower, the higher the concentration of volatile components,
while the decline in the closer tower bottom liquid, the more volatile rich, so as to achieve the purpose of separation. The gas rising from the top of the tower into the condenser, the liquid part of the condensate as reflux liquid return to the top of the tower into the distillation tower, the remainder is removed as the distillate.

The internal gas-liquid heat integrated distillation tower from the tower bottom liquid flowing part of liquid into the reboiler, heating evaporation into a gas phase back to tower, the other part of the liquid as residue removal, evaporator heat transfer area increases, resulting in gas-liquid film flow phenomenon, the basic principle of distillation is the liquid mixture multiple partial gasification and condensation, the components of different volatility characteristics, to achieve the purpose of separation distillation unit operation. According to its operation method can be divided into: simple distillation, flash distillation and special rectification. In recent years the emergence of super gravity distillation technology, using hundreds or thousands of times the gravity generated by high-speed rotation the super gravity field instead of the conventional gravity field, greatly enhance the gas-liquid mass transfer process, the height of mass transfer unit is reduced by 1 orders of magnitude. The huge tower equipment into a height less than 2 meters high gravity Rectification machine, increase efficiency, and reduce the volume. The internally heat integrated distillation column has changed the traditional model of distillation tower equipment, as long as the indoor factory can realize the continuous distillation process. The development of the society can save steel resources, extend the service life of the earth's resources. For the development of enterprises, can save space and space resources, reduce pollution emissions, improve product quality, improve management mode, reduce the labor intensity of production, increase production safety. However, the design of internal heat integrated distillation tower manufacturing technology is facing many problems: one is the manufacturing material must withstand low temperature, high pressure, corrosion resistance, abrasion resistance; two is the structure of heat exchanger is not only to ensure safe and efficient operation, and convenient maintenance. The three is to select the correct combination of theory and practice have a great influence on the heat transfer efficiency of the internally heat integrated distillation column The medium; four is the study of internally heat integrated distillation column liquid falling film flow and heat transfer theory, gas-liquid film flow drop theory is the fundamental basis of the distillation tower design, is the basis for optimization design of distillation column. In this regard, this paper studies the internal gas-liquid heat integrated distillation tower falling film flow phenomena, obtained by gas-liquid distillation column reduction film flow in saturated vapor pressure of liquidwater balance, using heat transfer equation and energy equation to balance the relationship between the circulating iterative gas-liquid falling film flow area, flow parameter information, at a given temperature, pressure conditions, the theory of gas liquid falling film flow optimal parameter values to achieve the best fit with the measured value, and the validity of the conclusion.

2. Theoretical analysis of liquid vapor balance in distillation column gas-liquid falling film flow

2.1. Physical model of gas liquid falling film flow in internal heat integrated distillation column

Figure 1 introduced the structure principle of internal heat integrated distillation tower, the structure of internal heat integrated distillation tower main evaporator, and condensers thermostat three heat exchanger, evaporator and condenser coexist in a large shell. Based on the blast furnace as heat source, medium gas and liquid propane as gasification medium for gas, each of which two kinds of refrigerant in the evaporator, the condensation heat transfer flow and temperature regulator, internally heat integrated distillation column in the heating process, the gas quantity control ignition temperature change, the change of temperature inside the heat integrated distillation tower flue, the internally heat integrated distillation column gas flow reverse regulation in the regulation process, often takes several hours to achieve changes in temperature feedback, the influence of time delay of control, resulting in internal heat integrated distillation column liquid falling film flow, in order to reduce the control delay of distillation tower, distillation tower to improve the control response speed, first in the heating mode, the pushing time, switching time and other aspects of discrete variable structure system control,
control regulation, analysis of liquid water balance mechanism, reservoir dynamic reserves of each period direct calculation of water drive gas using automatic fitting method dynamic, gas-liquid falling film regulation.

![Schematic diagram of internal heat integrated distillation column](image)

**Fig. 1** Schematic diagram of internal heat integrated distillation column

Figure 1 shows that the high temperature distillation liquid first into the thermostat, the temperature is TWA1, the flow inside the heat pipe in heat exchanger temperature regulator, outlet temperature of TWA2, then enters into the evaporator, further heat flows in the heating pipe of the evaporator, finally discharged from IFV, the temperature is TWA3; low temperature distillation liquid into the first the condenser, the temperature is T1, in the condensation heat exchanger tube flow and endothermic gasification, the outlet temperature is increased to T2, and then enter the thermostat flush liquid distillation tube bundle heat, the temperature increased further to design temperature T3; propane in the evaporator endothermic gasification, liquefaction in the condenser heat, so repeated cycles of heat transfer the saturation temperature constant is TPR.

2.2. Liquid equilibrium model for gas-liquid falling film flow

Assume that a period of water area by water is divided into n independent regions $G_{21}, G_{22} \cdots G_{2z} \cdots G_{2n}$, each region of the gas containing water were $W_{21}, W_{22} \cdots W_{2z} \cdots W_{2n}$ respectively, as shown in Figure 1. When production is not water pressure reducing, water gas expansion is not into the seal area, the expansion of the volume of material balance were $V_{21}, V_{22} \cdots V_{2z} \cdots V_{2n}$. Test independent areas secure seal area:

$$\sum_{i=1}^{n} \Delta V_i = \sum_{i=1}^{n} G_{2i} (B_g - B_{g1}) + \sum_{i=1}^{n} W_{2i}$$

(1)

And

$$\Delta V = G_2 (B_g - B_{g1}) + W_{e2}$$

(2)

The equation of mass balance without water seal zone is:

$$G_{p} B_g + W_{p} B_w = G_1 (B_g - B_{g1}) + W_{e1} + \Delta V$$

(3)
As you can see, in different periods of water influx in $W_{e1}$, $W_{e2}$, $G_1$, $G_2$ are in the air, change, but in the normal production of gas well without strong drainage period, the change tendency of the gas $G_1$ decreases, increasing water volume $G_2$, $W_{e2}$ increased continuously, until the water flooded wells.

The mass balance equations of the physical model of the gas-liquid falling film flow in the internal heat integrated distillation column are obtained by combining formula (5) and (6):

$$G_p B_g + W_p B_w = G_i \left(B_g - B_{gi}\right) + W_e + G_2 \left(B_g - B_{gi}\right)$$

(4)

Since the water invasion amount $W_e$ is consistent with the function of water invasion volume factor ($\omega$) and the degree of recovery ($R$), the conventional method is used to calculate:

$$\ln \omega = B \ln R$$

(5)

In the formula: $\omega$ is the volume coefficient of water invasion, $\omega = \frac{W_e - W_p B_w}{GB_{gi}}$; $R$ is the degree of recovery. By formula (7), it can be obtained:

$$1 - \frac{G_2}{G_1} = B \frac{B_{gi}}{G_{gi}} \left(1 - \frac{G_p}{G_i} + \frac{G_2}{G_i}\right)$$

(6)

The state parameters of the refrigerant in and out of each heat exchanger influence each other:

$$\varphi = \frac{1 - \frac{G_p}{G_i} + \frac{G_2}{G_i}}{1 - \left(\frac{G_p}{G_i}\right)^B + \frac{G_2}{G_i}}$$

(7)

Set, $A = \frac{10^8}{G_i}$, $C = G_2$, Then formula (10) becomes:

$$\varphi = \frac{1 - G_p A + C A}{1 - \left(G_p A\right)^B + C A}$$

(8)

In the formula, $\varphi$ is regarded as relative pressure; $A$ is the reciprocal of $G_i$ without water reserve; $B$ is the water penetration intensity of $W_{e1}$; and $C$ is the closed reservoir $G_2$.

3. **Automatic fitting method of mass balance**

The internally heat integrated distillation column of the three heat exchangers are separated independently establish a one-dimensional model, analyses the essence of automatic fitting algorithm is the parameter identification problem, namely, to seek the best fit with the measured values of the optimal parameters of the theoretical value, the deviation is minimum, it can be expressed as:
In formula: $\varphi_{\text{real}}$ is used to measure the apparent pressure in the process of production; $\varphi_{\text{theo}}$ is calculated as the theoretical value of (12) formula; $E$ is the objective function.

Formula (12) is an onlinear least squares problems. Using the automatic fitting method for fitting, a reasonable set of parameters of the objective function to minimize DFF, this paper uses the Complex method for automatic fitting. Because of two kinds of gas hydrate in the lattice filling performance caused by different initial conditions of hydrate formation change, change the V-H balance, therefore, in the evaporator heat integrated distillation tower, heat exchanger tube immersed in liquid propane, establish the balance system, the flow in the heat exchanger tube, tube outside heat absorption. The gasification of propane in the evaporator heat exchange tube is divided into 10 sections, each section for the following equation and relationship:

\[
E = \sum_{i=1}^{n} \left[ \varphi_{\text{theo}} \left( A_i, B_i, C_i \right) - \varphi_{\text{Measured}} \right]^2
\]  

(9)

In the condenser, vapor flow equilibrium hydrate heat absorption tube gasification, gasification steam heat. In Alkyl condensation in the heat exchange tube, the condenser in the heat exchanger tube is divided into 50 sections, each section for the following equation and relationship:

\[
\varphi_{\text{WA-EVAP}} = qm_{\text{WA}} (h_{\text{WA-EVAP}(i)} - h_{\text{WA-EVAP}(i-1)}); i=2-11
\]  

(10)

\[
\varphi_{\text{EVAP}} = k_{\text{EVAP}} A_{\text{EVAP}} \Delta T_{\text{EVAP}}; i=2-11
\]  

(11)

\[
\varphi_{\text{WA-EVAP}} = \varphi_{\text{EVAP}}; i=2-11
\]  

(12)

In the condenser, vapor flow equilibrium hydrate heat absorption tube gasification, gasification steam heat. In Alkyl condensation in the heat exchange tube, the condenser in the heat exchanger tube is divided into 50 sections, each section for the following equation and relationship:

\[
\varphi_{\text{LNG-COND}} = qm_{\text{LNG}} (h_{\text{LNG-COND}(i)} - h_{\text{LNG-COND}(i-1)}); i=2-51
\]  

(13)

\[
\varphi_{\text{COND}} = k_{\text{COND}} A_{\text{COND}} \Delta T_{\text{COND}}; i=2-51
\]  

(14)

\[
\varphi_{\text{LNG-COND}} = \varphi_{\text{COND}}; i=2-51
\]  

(15)

In the thermostat, water convection heat transfer in the tube, no liquid water, the decomposition temperature strongly depends on the water content of hydrate in gas phase, the thermostat in the heat exchanger tube is divided into 10 sections, each section has the following equation and relationship:

\[
\varphi_{\text{LNG-TERM}} = qm_{\text{LNG}} (h_{\text{LNG-TERM}(i)} - h_{\text{LNG-TERM}(i-1)}); i=2-11
\]  

(16)

\[
\varphi_{\text{TERM}} = k_{\text{TERM}} A_{\text{TERM}} \Delta T_{\text{TERM}}; i=2-11
\]  

(17)

\[
\varphi_{\text{LNG-TERM}} = \varphi_{\text{TERM}}; i=2-11
\]  

(18)

When calculating each heat exchanger independently, the decomposition temperature of hydrate decreases with the decrease of water content under the given pressure, and the independent calculation results need to satisfy the following formula of total energy conservation:
\[
\phi_{WA} = qm_{WA}(h_{WA1} - h_{WA3})
\]
\[
\phi_{LNG} = qm_{LNG}(h_{LNG1} - h_{LNG3})
\]
\[
\phi_{WA} = \phi_{LNG}
\]
\[
\phi_{WA-THERM} = qm_{WA}(h_{WA1} - h_{WA2}) = \phi_{LNG-THERM} = qm_{LNG}(h_{LNG3} - h_{LNG2})
\]

In the above, \( \phi \) represents the heat exchange obtained by using the energy equation, and \( \phi^* \) represents the heat transfer obtained by the heat transfer equation. \( qm \) represents the mass flow of the refrigerant, and \( h \) represents the enthalpy of the refrigerant.

The entrance temperature of TWA1 gas-liquid internally heat integrated distillation column is determined by the local climate conditions, the discharge temperature of TWA3 is too low, to meet the environmental requirements, it is also a constant effect on the internally heat integrated distillation column gas-liquid pressure \( p_{WA} \) changes on the physical properties of seawater is very small, it can be it is a constant; propane TPR temperature is not too high, otherwise it will contain the shell pressure put forward higher requirements, a one-time increase in the manufacturing cost of IFV. This equation has not closed, need to set a known quantity, the gas-liquid heat integrated distillation column discharge temperature thermostat Twa2 is a known quantity, the reason is the water flow is larger, the computational convergence is very sensitive to the change of Twa2, if Twa2 is unknown, Twa2 will give the initial value in the calculation of the beginning, the assumption of value must be very small difference between the true value and to make the calculation process converges smoothly, otherwise it will easily lead to the divergence of calculation results.

4. Parameter information calculation of gas liquid falling film flow in distillation column

The distribution model of heat transfer coefficient of building internal heat integrated distillation tower, the gas-liquid distillation falling film flow in the saturated vapor pressure of liquid water balance, at a given temperature and pressure conditions, by describing the heat transfer equation and energy equation:

\[
h = 90q^{0.67}M^{-0.5}P_r^n(-\log P_r)^{-0.55}
\]
\[
n = 0.12 - 0.2\log_{10} R_p
\]
\[
Nu = 0.021Re^{0.82}Pr^{0.5}
\]
\[

By using the heat transfer equation and the balance relation of energy equation, the parameters such as the area, flow and other parameters of the gas-liquid falling film flow are solved by cyclic iteration. The parameters and their setting values are obtained, as shown in Table 1.
According to the above parameters setting, according to the temperature difference between the heat integrated distillation column, analyzed the falling film flow characteristics of liquid vapor, liquid falling film flow theory makes the optimal parameters to achieve the best fit with the measured values of the heat integrated distillation tower falling film process is described as follows:

1) Temperature $T_{WA1}$, gas-liquid distillation falling film flow known $T_{WA2}$, $T_{WA3}$, $T_{LNG}$, $T_{LNG3}$ and $T_{LNG1}$ temperature, flow rate of $q_mLNG$, according to the energy conservation of the entire IFV system can be obtained by gas-liquid distillation falling film flow rate of $q_mWA$, according to the relationship of the thermostat in seawater and LNG energy conservation by temperature $T_{LNG2}$;

2) As an initial value for the ATERM area of heat thermostat, gas-liquid distillation falling film flow in assuming the thermostat in the uniform temperature for $\frac{T_{WA2}+T_{WA3}}{2}$, according to temperature thermostat in the process is divided into 10 sections, the heat exchange section, the value of temperature all known;

3) The heat transfer area of the first 9 sections is solved by the equilibrium relation between the heat transfer equation and the energy equation, and the heat exchange area is obtained by subtracting the heat exchange area of the first 9 sections with the initial total area;

4) Using the heat transfer equation and the heat balance equation to judge the heat balance relation, if not satisfied, then the heat exchange area of the thermostat is updated and returned 3) to be recalculated;

5) For the evaporator heat transfer area of initial value of $AEVAP$, propane saturation temperature is $TPR$, known, according to the temperature of the sea water, the evaporator heat pipe is divided into 10 segments, for the whole heat transfer section, the temperature of each point is known;

6) The calculation of the heat exchange area of a coherent heater, the heat transfer equation and the equilibrium relation of the energy equation are used to solve the heat transfer area of the evaporator by cyclic iteration;

7) For the condenser heat transfer area of initial value, propane saturation temperature is $TPR$, known, according to the LNG temperature, the condenser heat pipe is divided into 50 segments, for the whole heat transfer section, the temperature of each point is known;

8) The calculation of the heat exchange area of the coherent heater, the heat transfer equation and the balance equation of energy equation are used to solve the heat transfer area of the evaporator by cyclic iteration.

### 5. Experimental test analysis

In order to test this method on the internally heat integrated distillation column gas-liquid drop application performance analysis of membrane flow characteristics in the experimental analysis, Figure 2 shows the evaporator temperature, liquid propane and distillation temperature ($T_{WA}$, $TPR$ and $T$) along the curve in the horizontal coordinate diagram. FG is a dimensionless position, the corresponding Figure 2 from left to right, the evaporator heat exchange tube along the position; for rectifying the liquid from the condenser entrance to the exit of the heat exchanger tube along the position of propane in the housing. The uniform temperature is constant, so it is a straight line.
It can be seen that the distillation liquid in the evaporator temperature gradually decreased from right to left, due to the design requirements, the overall temperature of the distillation liquid drop is small, resulting in distillation liquid flow, liquid falling film distillation the same temperature in the evaporator is also very small decline; propane saturation temperature is close to the set value, the basic rectification the liquid in the evaporator temperature, higher set propane saturation temperature, IFV is conducive to the safe operation and can reduce the manufacturing cost of disposable liquid; distillation temperature gradually increased from left to right, in the entrance section of the temperature rise of a steep slope, which is due to the heat transfer in the entrance section of large temperature difference, heat is also high. With the heat transfer temperature decreases, the slope decreases gradually. The temperature rises with liquid distillation.

Figure 3 shows the temperature distribution of heat transfer temperature difference between inside and outside diameter, the abscissa $\beta$ is a dimensionless position for the diameter of the heat transfer temperature, the corresponding Figure 3 from left to right thermostat tube along the position. It shows the distillation temperature of the liquid from the entrance to the exit channel along the position.

Analysis shows that the geometry of gas-liquid internally heat integrated distillation column falling film flow heat exchange area and import column thermostat, the average temperature has a significant positive correlation between the entrance section of heat pipe temperature difference between inside and outside, the heat flux is larger, with the increase of internal heat integrated distillation column temperature, the slope decreases gradually rise the temperature map internally heat integrated distillation column corresponding to the temperature; the subscript WA said water, PR propane, EVAP
said COND said evaporator, condenser, THERM thermostat, heat exchange efficiency of the evaporator, condenser temperature regulator and a low of two appropriate heat transfer enhancement measures. The heat transfer efficiency of IFV. To enhance the overall heat transfer coefficient of the evaporator increases from left to right, mainly because from right to left, the water temperature gradually decreased, resulting in inside and outside the tube heat transfer coefficient decreased, and the heat transfer in the evaporator The flow of heat transfer inside and outside of the pipe with temperature variation is consistent, asymptotically linear curve of heat transfer of the evaporator, an increase of about 1000 \( \text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1} \); the heat transfer coefficient is increased gradually from left to right, the reason is that the LNG temperature increased gradually, leading to the surface of the heat exchanger tube temperature increases, the flow of heat transfer by condensation heat exchanger the heat pipe and the pipe heat transfer coefficient increased, while the heat transfer coefficient is also increased; the heat transfer coefficient of the thermostat from right to left in the entrance section gradually reduced, reducing slope, after the flat, the main reason is increasing with the internal heat integration of distillation temperature, exceed the critical temperature natural gas, heat capacity at constant pressure decreases with the increase of temperature, the thermostat heat transfer coefficient is mainly affected by the internal heat integrated distillation column pressure influence the change of heat capacity with temperature, changes appear as shown in Figure 4.

![Fig. 4 Gas liquid falling film flow in internal heat integrated distillation column](image)

It is similar to Figure 2, from right to left - internally heat integrated distillation falling film flow temperature drop is very small, so the geometric calculation process of gas-liquid heat exchange area in thermostat falling film import and the average temperature as the qualitative temperature influence on the result of calculation is very small, low temperature liquid falling film the temperature gradually increased from left to right, because the entrance section of heat exchange tube temperature difference between inside and outside, the corresponding heat flux is larger, with the increase of temperature liquid falling film, the slope decreases its temperature rise. The research results show that the geometry of gas-liquid internally heat integrated distillation column falling film flow heat exchange area and import column thermostat the average temperature has a significant positive correlation between the entrance section of heat pipe temperature difference between inside and outside, the heat flux is larger, with the increase of internal heat integrated distillation column temperature, the slope decreases its temperature rise, which accurately describes the internal heat integrated distillation. The characteristics of the gas liquid falling film flow in the tower are improved, and the heat transfer enhancement measures should be taken to promote the overall heat transfer efficiency.

6. Conclusion
This paper studies the internal gas-liquid heat integrated distillation tower falling film flow phenomenon, according to the distribution of gas-liquid mass balance internally heat integrated
distillation column independent region, distribution model of heat transfer coefficient of building internal heat integrated distillation tower, the gas-liquid distillation falling film flow in saturated vapor pressure of liquid level scale, using heat transfer equation and energy equation the balance between the cycle of iterative solution of gas-liquid falling film flow area, flow parameter information, at a given temperature, pressure conditions, gas-liquid flow falling film theory makes the optimal parameters to achieve the best fitting values with the measured values. The results show that the geometric gas-liquid internally heat integrated distillation column falling film flow heat exchange area and import distillation column thermostat, the average temperature has significant positive correlation, can accurately describe the gas-liquid heat integrated distillation falling film flow regularity, thereby reducing the pollution emissions from distillation tower, and improve product quality.

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