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Simulation Study on Heat Transfer Conditions Based on Vertically Descending Evaporating Tubes

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***Keywords*— biphasic flow, heat transfer conditions, numerical simulation, Vertical descending evaporation tube.**

***Abstract*— This paper aims to investigate the heat transfer conditions of vertically descending evaporator tubes. Through numerical simulation methods, the flow patterns and heat transfer characteristics within the evaporator tubes under both uniform and abnormal heating conditions are analyzed. Fluent software is employed to simulate the normal evaporation process in uniformly heated evaporator tubes, exploring their gas circulation and local heat transfer conditions. Additionally, simulations are conducted for descending evaporator tubes under abnormal heating to analyze the impact of different heat distributions on the flow patterns and heat transfer within the tubes. The conclusion drawn is that the primary cause of working fluid descent in evaporator tubes is uneven heating of the tube bundle. A single evaporator tube forms a stable circulation, whereas an increase in the number of tubes in the bundle exacerbates the descent phenomenon. To prevent such occurrences, measures such as optimizing heat transfer, ensuring complete combustion, and regularly maintaining the pipelines can be implemented. Future research could further simulate real-world boiler heating conditions and explore the application of two-phase evaporation flow in other equipment.*

I. INTRODUCTION

At the 75th session of the United Nations General Assembly, the Chinese government pledged to enhance nationally determined contributions by adopting more robust policies and measures to strive for peaking carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060. This policy aims to tackle global climate change, reduce greenhouse gas emissions, promote green development, and protect the ecological environment. Nowadays, energy issues have become a focal point of societal attention, and the proposal of the "dual carbon" goals poses a challenge to the expansion of traditional energy sources. The latest data shows that by the end of July 2024, China's total installed power generation capacity reached 31.0 billion kilowatts, representing a year-on-year growth of 14%. Among this, solar power generation capacity was approximately 740 million kilowatts, up 49.8% year-on-year, while wind power generation capacity was around 470 million kilowatts, up 19.8% year-on-year. From January to July 2024, thermal power generation capacity totaled 14,106.1 billion kilowatts, a year-on-year increase of 3.5%. By the end of July 2024, thermal power's cumulative installed capacity accounted for 45.46% of the nation's total installed power generation capacity. The installed power generation capacity continues to grow, with wind and solar power exhibiting particularly strong momentum. However, despite the rapid development of renewable energy, given the current energy structure and actual demand, thermal power generation cannot be abruptly abandoned or significantly reduced in the short term. For some time to come, thermal power will continue to play a crucial role in electricity supply, with its stable output capacity and mature technological system being indispensable for ensuring national energy security and stable economic operation.[1]

As a crucial pillar of thermal power generation, boilers are not only the starting point of energy and power conversion but also the core process of converting the chemical energy of fuel into internal energy. During combustion in the boiler, the fuel within the furnace releases a significant amount of heat. This heat is transferred to the water-cooled walls through radiation and convection, thereby facilitating the evaporation of water into steam.[2] During the operation of the boiler, heat continuously accumulates and transfers within the furnace. At this point, to achieve further energy conversion and utilization, evaporator tubes, a crucial component, are needed to convert water into steam. Evaporator tubes play a vital role in the boiler system, acting like an energy transmission channel that converts the heat generated by the boiler into powerful steam, providing continuous power support for subsequent power generation processes or other industrial applications.

The production of qualified steam by evaporator tubes is influenced by various factors, including working temperature, properties of the liquid working medium, flow rate and temperature of the supplied liquid, ambient humidity, stability of the heat source, internal structure of the heat tubes and liquid circulation status, external environmental temperature and pressure, as well as the design and manufacture of the evaporator tubes.[3] Additionally, evaporator tubes find extensive applications in numerous modern industrial sectors. For instance, in the paper industry, evaporators are used to concentrate pulp during the paper production process and to dry paper with steam, thereby producing high-quality paper products. In wastewater treatment, facilities such as urban wastewater treatment plants utilize evaporators to evaporate and recover water from wastewater, achieving the goals of water conservation and reducing wastewater discharge. In seawater desalination, evaporators are employed to evaporate seawater, removing salts and impurities to obtain usable freshwater.[4] In the solar energy sector, water is heated and converted into steam to generate electricity or achieve water cycle heating. With the development needs of modern industry, the performance of evaporators is continuously being improved to better meet the demands of various sectors.

Currently, it is observed that evaporation tubes experience heat transfer deterioration when subjected to excessive or insufficient heating. When the tube wall is heated with a constant heat flux, as the heat flux increases, according to heat transfer theory, there exists a critical heat flux density for constant heat flux heating. At this point, the boiling states experienced by the water inside the tube include subcooled boiling and nucleate boiling. When the heat flux density on the tube wall exceeds the critical heat flux density, the boiling of the water inside transitions to film boiling. At this stage, due to the increased presence of gas near the tube wall, heat transfer becomes less efficient than in the previous stage, causing the wall temperature to rise rapidly. If boiling continues, when it reaches the mist stage, the adhering water film is evaporated, and the excessive gas once again leads to heat transfer deterioration.[5] On the other hand, insufficient heating issues caused by various factors such as combustion or structure are also relatively common. These issues are mainly manifested as heat discrepancies between the water-cooled walls or among the evaporator tube bundles. In particular, evaporator tubes that are less heated may experience circulation stagnation, free water levels, and reverse circulation.[6] For many riser tubes in the boiler's evaporation water cycle, the heat they receive is not entirely uniform but rather uneven. When uneven heating occurs, the amount of steam generated and the temperature within the tubes due to heating also become uneven, leading to uneven pressure distribution and subsequently uneven flow velocities within the tubes. When this uneven heating reaches a certain level, circulation stagnation or even reverse flow phenomena may occur, and for horizontally placed tubes, steam-water stratification may arise.[7]

Currently, research on fluid flow in pipes has become a hot topic, encompassing aspects such as fluid flow patterns and heat transfer conditions. However, most studies focus on the flow and heat transfer of fluids in horizontal pipes, while research on vertical pipes is relatively scarce, especially regarding heat transfer in vertical pipes under uniform heating boundary conditions. Typically, analyses of fluid heat transfer in vertical pipes are predominantly based on single-phase fluid studies, whereas research on multiphase fluids mostly remains confined to horizontal pipes.[8] For instance, the flow of refrigerant working medium in air conditioning evaporators and the condensation process of refrigerant vapor in horizontal heat exchange tubes in condensers are relevant examples. The reverse flow caused by uneven heating of evaporator tubes poses significant obstacles to the normal operation of the boiler's water cycle and its daily work. In practice, this issue has been addressed through actual experimentation, but there is still limited research exploring this problem from a simulation perspective.

The research approach in this paper starts with real-world problems, integrating knowledge from heat transfer, fluid mechanics, and boiler principles. Utilizing the Fluent module in ANSYS 2022 R1 for simulations, it will explore the vapor-liquid two-phase fluid flow patterns in evaporator tubes experiencing insufficient heating and the development of descending flows. Additionally, the relationship between heat flux density and thermal conductivity will be considered.

II. INTRODUCTION TO THE MAIN MODELS

The evaporation tubes, steam drum, downcomers, headers, and connecting pipes in the boiler evaporation equipment were selected for modeling. The model was simplified primarily with reference to the relevant chapters on natural water circulation in textbooks on power plant boiler principles, in order to highlight the key research objects. Simplified models were created for the evaporator tube bundles, steam drum, downcomers, and headers. For example, only the pipe models were depicted for the evaporator tube bundles, which were assumed to be of the plain tube type, and most of the other structures and internal steam-water separation structures in the steam drum were omitted. The following figure provides a rough conceptual illustration of the geometric modeling:

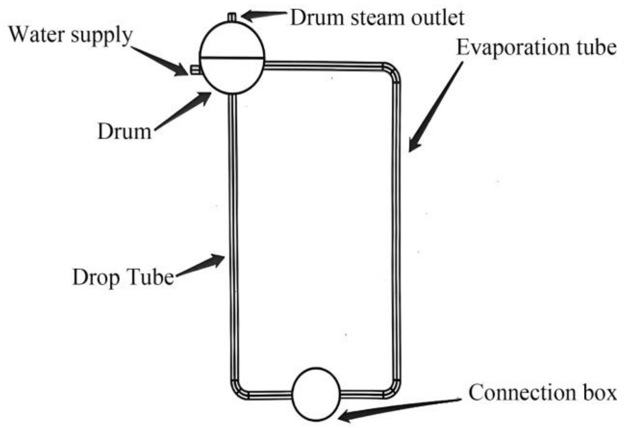

Fig.1：Roughness diagram of geometric modeling

III. SIMULATION OF WORKING FLUID FLOW IN A UNIFORMLY HEATED EVAPORATOR TUBE

3.1 Simulation of normal evaporation in a uniformly heated evaporator

Before further investigating the abnormal conditions of the evaporator tubes, the normal evaporation water cycle was first simulated. A single tube was selected for the simulation, with the middle section cross-section observed to examine the flow patterns inside the tube. Additionally, this study falls under the category of unsteady-state research. For multiphase flow, the Mixture model was chosen in this study based on the fluid properties of boiling heat transfer within the tube.

The uniformly heated evaporator tube circulation system was considered as an open system with mass and energy exchanges with the outside environment. The mass inlet was the water supplied by the feedwater pump, which was delivered to the lower inlet of the steam drum. The corresponding inlet in the model was set as a mass flow inlet with a mass flow rate of 300 kg/m³. Since the water from the feedwater pump passes through the deaerator and economizer, it has a higher temperature, and the mass flow inlet temperature was set at 50℃. The mass flow outlet was the steam discharged from the upper outlet of the steam drum. The steam discharged from the steam drum needs to pass through the superheater and reheater to meet specified requirements before entering the turbine. Therefore, a pressure outlet was set at the outlet surface of the steam drum in the model. The pressure outlet boundary condition defined the static pressure at the outlet boundary of the flow field. The static pressure value was used when the flow field was subsonic, while the pressure was interpolated from within the flow field when the outlet reached supersonic speeds. The backflow conditions were set as close as possible to reality to ensure the convergence of the calculation. For heat input, due to the uniform heating of the evaporator tube, a constant heat flux density was directly set using the wall condition in the boundary conditions. Based on the data, the specific heat value for the single evaporator tube wall in this simulation was 10,000 W/m².

3.2 Solve and calculate

For the discretization scheme, Fluent solves the governing equations of the flow field to obtain the values of flow variables at all control points. The method used in the computation process for this solution is the QUICK (Quadratic Upwind Interpolation for Convective Kinematics) scheme. The QUICK scheme provides values at boundary points using a mixed form of weighting and interpolation. The QUICK scheme was originally proposed for structured grids (i.e., quadrilateral grids in two-dimensional problems and hexahedral grids in three-dimensional problems), but in Fluent, the QUICK scheme option can also be used for unstructured grid calculations. In unstructured grid calculations, if the QUICK scheme is selected, the values at non-hexahedral (or non-quadrilateral) edge points are computed using the second-order upwind scheme. The QUICK scheme offers higher accuracy when the flow direction aligns with the grid orientation. Therefore, the QUICK scheme was chosen for this study.[9][10]

Since the upper half of the steam drum contains a constant presence of gas, local initialization is required. A specific grid region within the steam drum (which has been previously meshed) was selected, and by setting the gas volume fraction to 1, it was maintained as a gaseous region.

IV. SIMULATION OF A DESCENDING EVAPORATOR TUBE UNDER ABNORMAL HEATING

My main objective is to simulate the occurrence of reverse flow in a uniformly heated evaporator tube using numerical simulation methods and compare it with the normal circulation flow conditions. Through simulation, I aim to seek answers to the problem of reverse flow in the evaporator tube. The working conditions inside a uniformly heated evaporator tube under normal circumstances have already been determined. The next step is to conduct a simulation analysis of abnormal conditions with uneven heating. The geometric model used here is the previously mentioned evaporator tube bundle consisting of three tubes, and a preliminary comparison of the flow patterns in the evaporator tube during descent under abnormal conditions with those under normal conditions will be made. To better represent abnormal conditions, a subsequent simulation using an evaporator tube bundle consisting of 10 tubes will be conducted.

In the three-tube model, the mesh size for the lower part of the steam drum and the header is relatively large, approximately 0.01. Since the evaporator tube is the focus of the study, a smaller mesh size of about 0.001 is used for division. For the gas part of the steam drum, the unit mesh size is about 0.002. The remaining non-critical components adopt automatic mesh generation by the system to save space and reduce equipment pressure. Ultimately, the number of mesh elements in this model is approximately 650,000.

When entering the Fluent solver, the environment settings, solver configuration, solution method, relaxation factors, and initialization are the same as those for the single-tube model. However, the boundary condition settings are different. For the three-tube model, the boundary conditions that need to be adjusted include the mass flow rate at the system inlet and the heat received by each tube. The solution settings and initialization remain consistent with those used previously.

4.1 Simulation results

The following is a nephogram of the results of the three evaporation tubes:

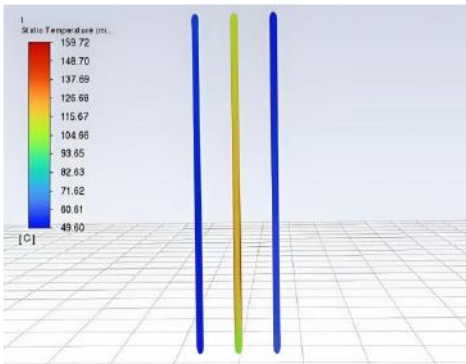

Fig. 2: Profile temperature nephogram of three root canals

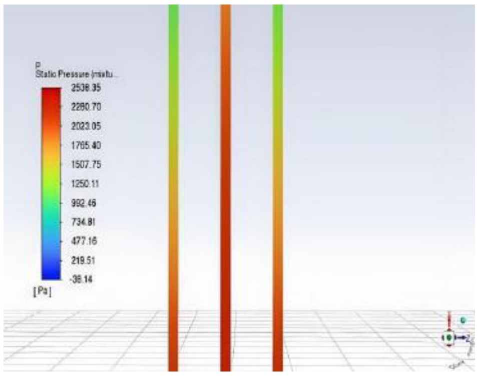

Fig. 3: Profile pressure nephogram of three root canals

4.2 Simulation results of three-tube model with different heat distribution

For the phenomenon of descending evaporator tubes, due to variations in uneven heating of the evaporator tubes, different heat distributions will be used to simulate as many scenarios as possible, in order to obtain more diverse patterns for convenient comparison and summarization. The following are the boundary conditions:

Table.1: The setting of boundary conditions for each tube:

Example	Heat of the first tube	Heat of second root canal	Third root canal heat	Inlet flow of water supply
Case1	18000w	8000w	5000w	400L/m²·s
Case2	12000w	12000w	6000w	400L/m²·s
Case3	8000w	8000w	5000w	400L/m²·s

The simulation results are shown below

Case 1: 1.8W heat + 0.8W heat + 0.5W heat, with a water flow rate of 400L/m²·s

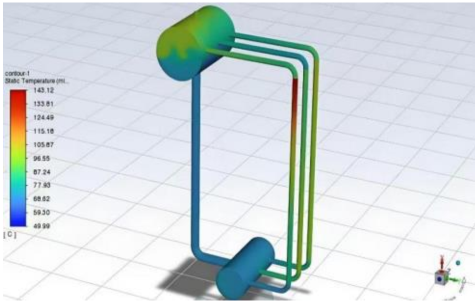

Fig. 4: Temperature nephogram

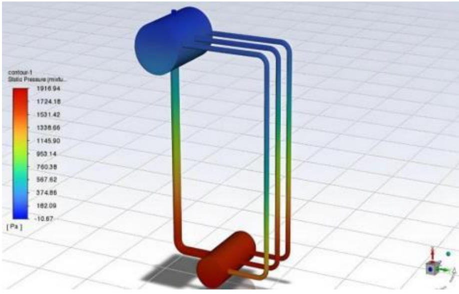

Fig. 5: Pressure nephogram

Case 2: The first two have a heat output of 1.2W, and the last one has a heat output of 0.5W, with a water flow rate of 450L/m²·s.

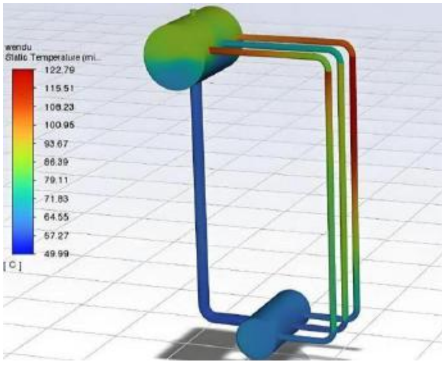

Fig. 6: Temperature nephogram

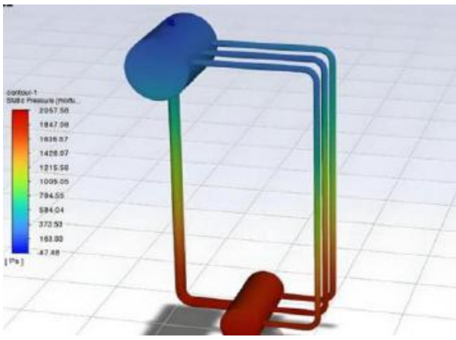

Fig. 7: Pressure nephogram

Case 3: The first two have a heat output of 1.0W, and the last one has a heat output of 0.7W, with a water flow rate of 400L/m²·s.

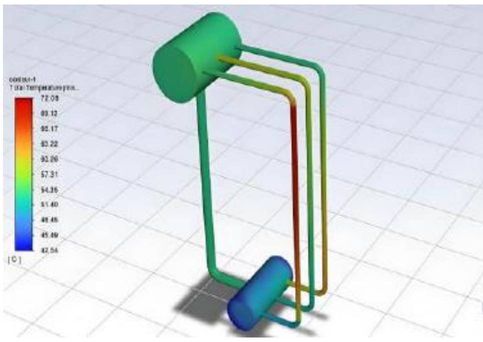

Fig. 8: Temperature nephogram

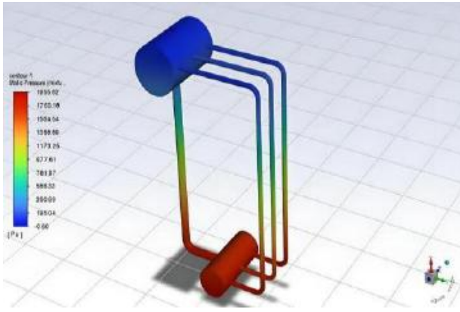

Fig. 8: Pressure nephogram

4.3 Simulation of descending evaporator tubes in a ten-evaporator tube bundle

To better represent the uneven heating of evaporator tube bundles in reality, a model with ten tubes is used for simulation. First, a simulation of uniform heating is conducted, assuming that each tube receives the same amount of heat to achieve normal heating results. The mass inlet is set to 700kg/m²·s, and the pressure outlet is set to a pressure reflux of 99 degrees Celsius. The boundary conditions for wall temperature heating are the same as before. A simulation of uneven heating of the ten tubes is then conducted, with other settings remaining the same as above, except for different boundary conditions.

In this scenario, the flow rate for all ten tubes is set to 700kg per square second. The heat input for the first tube is 6000w, while the heat input for the second to the ninth tubes is 12000w. Specifically, the heat input for the tenth tube is set to 10000w.

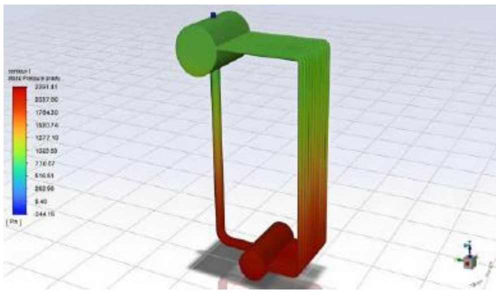

Fig. 9: Pressure nephogram of uneven heating in a ten-tube configuration

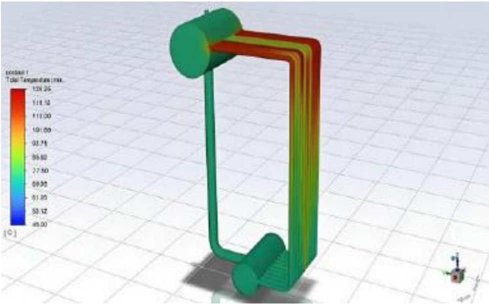

Fig. 10: Temperature nephogram of uneven heating in a ten-tube configuration

It can be observed that in cases of uneven heating, if the water level in the boiler drum is too low, or if there are significant fluctuations or excessively low water levels, it can lead to the formation of a vortex funnel at the inlet of the downcomer. This vortex funnel can "draw in" steam into the downcomer, which reduces the density of the working fluid in the downcomer and subsequently lowers the circulation head.

V. SIMULATION RESULTS AND DISCUSSION

For the two-phase flow of steam and water in the downcomer, the single-phase water velocity distribution in the cross-section of the vertically ascending tube is highly uneven. Specifically, the water near the wall flows slower due to the effect of water viscosity, while the water at the center of the tube flows fastest. When water near the tube wall absorbs heat and generates bubbles, these bubbles are propelled upwards by buoyancy, causing them to move faster than the water. The bubbles close to the wall, influenced by the slower flowing water nearby and the faster flowing water at the center of the tube, will migrate towards the center, resulting in the bubbles, like the water, moving faster at the center than at the edges.[11] This phenomenon is attributed to the combined effects of buoyancy and water flow. If either of these two forces produces a different effect—for instance, if the water flow direction is reversed—then, following the same principle, the water flow would be ahead of the bubbles. These slower-moving bubbles would also be pushed away from the center of the pipe under the influence of the swirling flow.

(1)The Nusselt number calculation equation at this time is:

$$N\mu = 0.023Re^{0.8}Pr^{0.4}\left(\frac{n_f}{n_w}\right)^{0.11} \quad (1)$$

Where Re is the Reynolds number, and the characteristic radius is the radius of the heated evaporation tube (22); Pr is the Prandtl number; n_f , n_w represents the viscosity of the fluid and the wall.

As the water near the tube wall absorbs heat and its temperature rises to the saturation temperature, local bubbles are generated. However, much of the water has not yet reached the corresponding temperature, resulting in subcooled nucleate boiling at this stage.[12] When all the water in the tube has absorbed heat from the tube wall, it enters the second stage of boiling heat transfer—nucleate boiling. At this point, bubbles gather at the center of the tube to form steam slugs, which are separated by layers of water. As the water between the steam slugs absorbs more heat and evaporates during its upward journey, the steam slugs merge into a ring-shaped formation around the tube. Subsequently, the fluid inside the tube further absorbs heat, and the water film left on the wall due to viscosity also turns into gas. At this stage, the steam appears as a mist, which still contains moisture and can continue to absorb heat until the last trace of water vapor disappears, and the steam inside the tube becomes a single-phase fluid again.

The simulation results for a normally operating, uniformly heated evaporation tube are as follows:

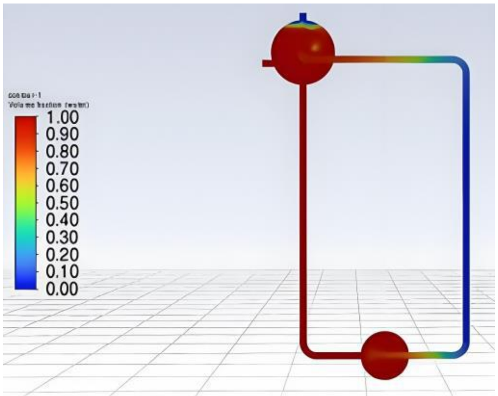

Fig. 11: Volume fraction nephogram of uniformly heated tube

As can be seen, after the evaporation tube on the right side is heated and generates gas, the gas initially flows up and down without forming a circulation. When the conditions are met, the fluid (gas) with a smaller volume fraction in the evaporation tube begins to flow upward, while the red fluid (water) on the left flows downward through the header and towards the heated tube. At this point, the gas in the evaporation tube rises to the steam dome, and the gas-liquid interface remains at a stable position. The flow pattern analysis inside the evaporation tube is similar to the data for uniformly heated tubes.

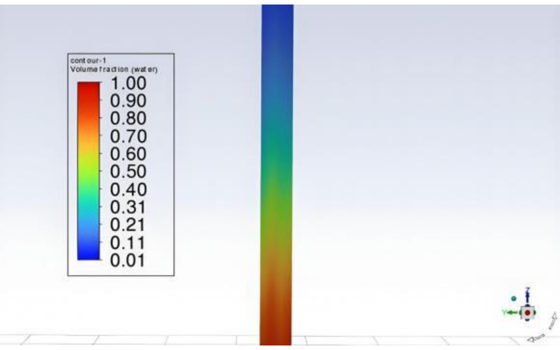

Fig. 12: Water volume fraction distribution diagram for a uniformly heated tube

As can be seen, for a normally operating, uniformly heated evaporation tube, the water volume fraction nephogram shows a distribution from 100% inside the tube to 0.01% at the top of the tube, which is quite consistent with this situation. Of course, for the superheated steam mentioned above, in the boiler water process, it needs to leave the steam dome and pass through the reheater and superheater for further heating before it can become the superheated steam required by the steam turbine.

This process can also be analyzed in engineering thermodynamics. When unsaturated water that has not reached the saturation temperature at the corresponding pressure is heated, the thermal motion of the water molecules intensifies, the temperature rises; and the specific volume increases. When the saturation temperature is reached, the water begins to vaporize, with the saturation pressure and temperature remaining constant. If heating continues, the amount of water decreases, the amount of gas increases further, and the water volume fraction decreases as it moves upward until it all turns into water vapor. At this point, the steam is called dry saturated steam. If this steam is further heated into the superheated stage, the heat absorbed at this time is superheat. However, since the inside of the tube is all gas, heat transfer is not as efficient as it was with the previous liquid, which can cause the wall temperature to rise rapidly, potentially damaging the equipment. Finally, the dry saturated steam absorbs heat, and its temperature exceeds the saturation temperature, becoming superheated steam.

From the temperature contour plot, it can be observed that the temperature continuously increases as heat is absorbed from the bottom to the top of the tube, reaching its peak as steam at the final stage. The temperature at the topmost part can reach close to 200 degrees Celsius, indicating that the gas there is likely superheated steam. Comparing it with the volume fraction plot, it is found that the water volume fraction at the corresponding position is 0, confirming it as superheated steam. If the water volume fraction is not exactly 0 but close to 0, it is highly likely that there is still a partial water film present. If the tube is completely filled with gas, the heat loss and thermal damage to the tube wall can be severe. The enormous heat cannot be promptly absorbed by the working fluid, leading to deterioration of the tube's performance and potential harm to the equipment.[13]

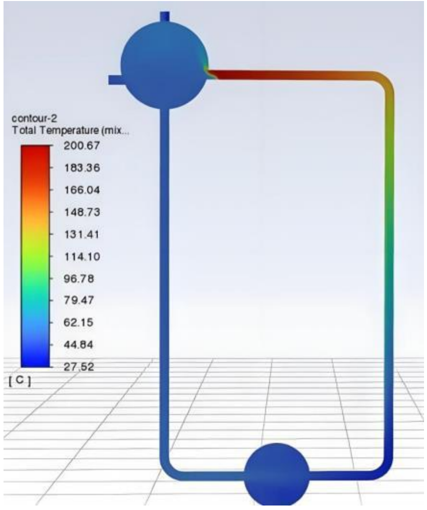

Fig. 13: Temperature nephogram of a uniformly heated tube

Under normal conditions, as previously mentioned, the flow pattern distribution from the bottom to the top of the tube is as follows: single-phase liquid → bubbly flow → slug flow → annular flow → single-phase gas.[14][15] The surface heat transfer coefficient during this process should first increase and then decrease. Specifically, it increases continuously from liquid convection heat transfer to annular flow. When it reaches single-phase gas flow, the liquid film on the tube wall completely evaporates, leaving only gas in contact with the tube wall. The thermal conductivity (Nu) of gas is relatively smaller than that of liquid. Therefore, when the difference in Nu is not significant, the surface heat transfer coefficient is smaller than that of gas.

Next, we simulate a descending evaporation tube with uneven heat transfer. From the temperature nephogram, it is clearly visible that the second tube is filled with steam and has a higher temperature than the other two tubes, reaching 150°C, which is consistent with the volume fraction nephogram showing that it is mostly steam. The temperature of the first tube is about 80°C. From the volume fraction nephogram, it can be seen that it is heated well, with some steam already entering the steam dome. At this time, most of the fluid inside the tube is subcooled water, resulting in a lower temperature. The third tube is significantly underheated (4000W), with much of the water inside the tube not reaching the saturation temperature due to insufficient heat absorption. The overall temperature of this tube is lower than the first two and close to the temperature inside the descending tube, indicating severe underheating.

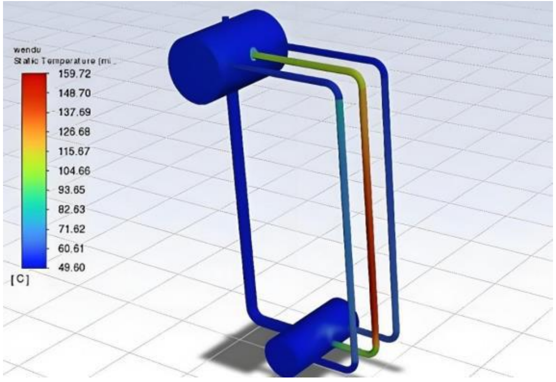

Fig. 14: Temperature nephogram of an abnormally heated evaporation tube

Due to the different heat reception conditions of the evaporation tubes, the most directly affected are the non-flowing working fluids inside each tube. Therefore, in the post-processing of this simulation, a sectioning method is adopted to analyze the evaporation tubes with different heat reception conditions through the sectioning of nephograms.

Firstly, let's analyze the evaporation tube with a heat reception of 15000W. As shown in the figure, it is the first tube from the top. From the figure, it can be seen that starting from the bottom of the evaporation tube (from left to right), there is initially forced convection heat transfer between the liquid and the tube wall. Subsequently, as the water temperature rises to the saturation temperature, bubbles are generated, and the water volume fraction begins to decrease to the range of 0.8 - 0.9. Then, with further heating of the tube wall, the gas inside the tube gradually increases, which is basically in line with the flow pattern of a normally heated evaporation tube.

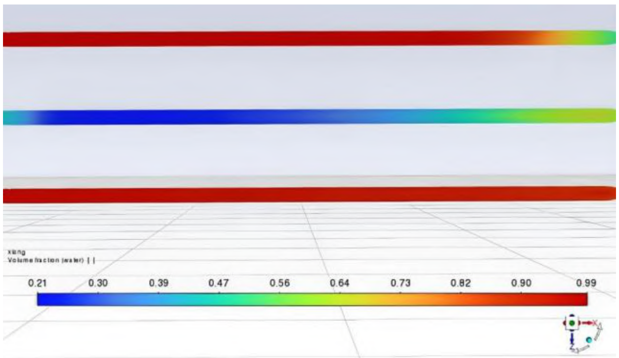

Fig. 15: Sectional volume fraction of three tubes with uneven heat distribution

Secondly, for the second tube, it can be seen from the volume fraction diagram that the gas content is higher near the tube wall. The water flow at the upper part of the tube (as shown on the right side of the figure) has not yet vaporized and is still in a liquid state. From this, it can be inferred that the liquid here is flowing downwards. The downward-flowing liquid will also generate gas after being heated by the tube wall, but the gas is carried downwards, causing a large accumulation of gas at the bottom of the tube. If the pressure here is greater than the pressure in the descending tube, the gas will enter the header.

At the same time, from the perspective of pressure, the pressure in the second tube is generally higher than that in the first and third tubes. This is because there is a large amount of steam flowing downwards in the second tube at this time. Due to insufficient heating, the working fluid in the third tube remains in a liquid state, and the pressure is relatively stable.

When there is a downward flow of heat in the evaporation tube, due to the upward buoyant force on the vapor bubbles, the vapor bubbles will only be carried downwards when the water velocity is greater than the upward floating velocity of the vapor bubbles.[16] Therefore, the flow pattern of downward water flow in the evaporation tube caused by uneven heat distribution, especially the flow pattern changes occurring during the downward flow process, will be influenced by the bubble velocity and water flow velocity. In view of this, the article presents the velocity nephogram of the simulation below.

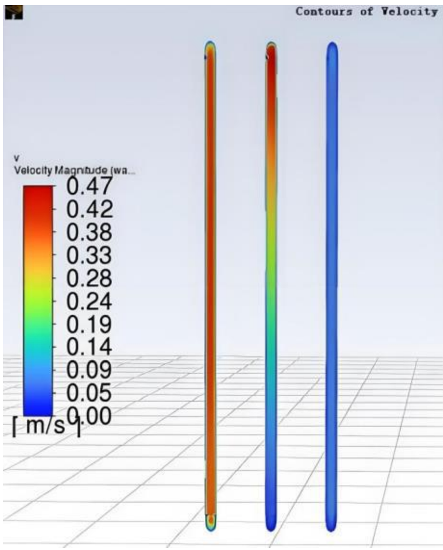

Fig. 15: Liquid velocity in the three tubes

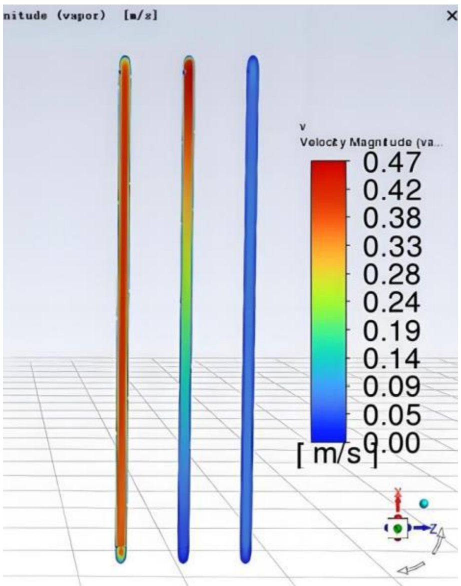

Fig. 16: Gas velocity in the three tubes

The sections of the first, second, and third tubes are shown from top to bottom in the figure. It is clearly visible from the figure that due to the scarcity of liquid and abundance of gas in the second tube, there is more liquid in the first and third tubes.

$$\mathrm{h} = \frac{N_{\mu}\lambda}{\mathrm{d}} \quad (2)$$

Furthermore, considering that the thermal conductivity of liquids is greater than that of gases, it can be inferred that when Nu is the same (the expression for Nu is the same for boiling heating inside the tubes), the surface convection coefficient of gases is larger than that of liquids. Therefore, the overall heat transfer rate is not as good as in the first three tubes, and the heat transfer efficiency of the second tube is very low.

After the previous comparisons, we have contrasted several heat transfer conditions of evaporation tubes under normal and abnormal operating conditions, and also conducted a simple flow pattern analysis incorporating knowledge of two-phase flow.

For normal heat reception, the heat received by each tube is consistent. Due to uniform heat reception, the flow patterns and distribution of state parameters within the uniformly heated tubes are similar. The main manifestations are: the heated liquid water within the tube with uniform heat flux density gradually produces steam after subcooled boiling and nucleate boiling. The bubbles rise under the influence of buoyancy and viscous forces. The upward steam is still heated by the wall heat flux, but the heating conditions are different. This is mainly manifested by the presence of gas-liquid mixture at the bottom and mostly gas at the top, which causes the upper part of the gas to gradually heat up and eventually become superheated steam under heating.

For the situation caused by abnormal heat reception, the first reason is that the excessive difference in heat reception among the evaporation tube bundle leads to excessive pressure in the tubes, causing uneven pressure and resulting in the downward flow of water in some tubes under the influence of pressure. This part of the tubes flowing downward will still undergo the aforementioned boiling stages under uniform wall temperature heating, transitioning from liquid to gas. Finally, the downward-moving gas appears in the lower header. The difference from the above is that during the downward process, bubbles generated when the water is heated to saturation temperature move upward under the influence of buoyancy and gravity. However, the water flow direction at this time is opposite to the normal situation, so the direction of bubble movement is inconsistent with the normal situation.

For the abnormal situation where the reverse flow of steam caused by uneven heat reception in the evaporation tubes is heated and moves downward, the main reasons are uneven heat reception in the evaporation tubes, excessive resistance in the descending tubes, and excessive pressure changes. Measures can be taken from both structural and operational aspects.[17]

Structural measures include: (1) Dividing the circulation loops based on heat reception conditions; (2) Improving the heat reception conditions of the tubes at the four corners of the furnace; (3) Enhancing heat transfer by adding structures such as fins and using threaded tubes; (4) Adopting a simple layout for large-diameter descending tubes to minimize stress on the piping.

Operational measures that can be implemented include: (1) Selecting a larger ratio of descending tube cross-sectional area to ascending tube cross-sectional area to reduce the flow velocity of the working fluid in the descending tube; (2) Improving combustion efficiency and regularly cleaning the surface of the tubes; (3) Paying attention to monitoring pressure changes.

VI. CONCLUSION

This study begins with heat transfer simulation to model the different heating conditions of the evaporator tube bundle in a boiler evaporation model. By simulating scenarios where each tube is uniformly heated and then analyzing the flow patterns and heat transfer conditions of each tube in an abnormal situation involving a three-tube evaporator bundle, this paper aims to provide insights. Ultimately, it is concluded that there are various reasons for the decline in working fluid in evaporator tubes, with one significant cause being the uneven heating among the evaporator tube bundles. For a simple cycle composed of a single evaporator tube, the system is highly stable, and the two-phase flow patterns align with existing boiling conclusions. However, as the number of tubes in the bundle increases, the decline in evaporator tube performance becomes more pronounced. The uneven pressure not only leads to a decline in evaporator tube performance but also causes gases to descend in the downcomer. The primary methods to prevent such situations include reducing abnormal heating of the evaporator tubes, optimizing heat transfer, ensuring adequate combustion in the boiler, regularly maintaining the pipelines, or reducing the resistance in the downcomer.

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