Intensification of heat transfer during condensation of water vapor on a vertical tube

Lutfulla Eshkuvatov[1]*, *Rakhimjan* Babakhodjayev[1] and *Nazim* Tashbayev[1]

[1]Tashkent State Technical University, University str. 2A, 100095 Tashkent, Uzbekistan

Abstract. A review of the scientific literature on the intensification of the heat exchange process during condensation of water vapor on the surface of a vertical tube is carried out and the main results of the study are presented. The work on the study of heat transfer during laminar condensation of water vapor in the form of a laminar-flowing liquid in the form of a film both inside and on the outer surfaces of vertical tubes with an ascending steam flow is analyzed. The numerical values of Nusselt and Reynolds, which are also known and proposed for the case under consideration, have been studied. Methods of intensification of the heat exchange process are presented by improving the geometric configuration of the heat exchange surface from the side of the heating steam, on which its condensation occurs during heat transfer, which consists in reducing the thermal resistance of the wall molecular layers of the liquid. This method helps to increase the coefficient of heat transfer from steam to the wall surface by increasing the surface area of heat exchange. Based on the study of the results of well-known works, the authors have developed an experimental laboratory installation to study the increase in the efficiency of water vapor condensation processes on the outer surface of a vertical tube. An important scientific problem to be solved is the breakdown of the laminar-flowing liquid of condensed steam from the heat exchange surface, which leads to the admission and contact of steam directly from the cold surface of the tube.

1. Introduction

In the world, special attention is paid to research in the field of creating competitive technologies that meet international requirements, efficient designs of heat exchange plants for various industries of heat power, chemistry, food and oil refining industries.

The intensification of heat exchange processes leads to a decrease in the size and mass of heat exchangers with an increase in their thermal power, which is a very relevant issue.

The work in question is devoted to the development of a laboratory stand for the study of the condensation of water vapor in a shell-and-tube heat exchanger. This issue is considered in many published works, where various methods and methods are proposed that lead to improved heat transfer during condensation of heating steam in tubular apparatuses [1-7].

It is known that with abundant condensation of heating steam, the condensate forms a liquid film on the surface of a vertically positioned tube and, as it flows down, the thickness of the condensate layer increases, which increases the thermal resistance affecting the heat transfer process [8-17].

Heat exchange during the laminar flow of the condensate film inside vertical tubes with an ascending steam flow has been theoretically investigated in [9-13]. The condensation of the return flow inside a closed thermosiphon is analytically considered in [9]. In these papers, the results obtained were compared with the classical Nusselt theory for the case of a stationary steam.

A number of works are devoted to the condensation of steam in the form of a laminar film inside a pipe for the cases of ascending and descending turbulent steam flow [9], the theoretical study of the condensation of an ascending steam flow in the form of a laminar- fluid in a vertical tube [14], analytical study of condensation of the reverse flow of steam in a two-phase closed thermosiphon taking into account the influence of interphase shear stress [15], mathematical model of heat transfer during steam condensation taking into account mass transfer, steam velocity and

---

*Corresponding author: lutfulla-86@mail.ru

interphase shear [16], mathematical model for condensation of the reverse flow of current vapors taking into account non-condensable gases which are present in real operating conditions of heat exchangers and with this the results of the work are of interest to specialists [17-21].

2. Materials and Methods

The purpose of this work is to develop an improved laboratory installation to increase the efficiency of heat exchange processes during condensation of water vapor on a vertical heat exchange tube with various geometric intensifying surface shapes. Intensification, in essence, consists in reducing the thermal resistance of the wall layers, which contributes to an increase in the heat transfer coefficient by increasing the heat exchange surface area. Finned surfaces, which are used in most heat exchangers, provide an effective increase in the heat transfer surface area. The use of a peculiar design of finned surfaces also allows you to influence the flow of the coolant, disturbing it.

Figure 1 shows the developed scheme of an experimental laboratory stand for the study of heat exchange processes during condensation of heating steam on the surface of vertically arranged tubes.

To study the process of steam condensation on a vertical tube with an improved fin surface, an experimental setup was developed and created (Fig. 1).

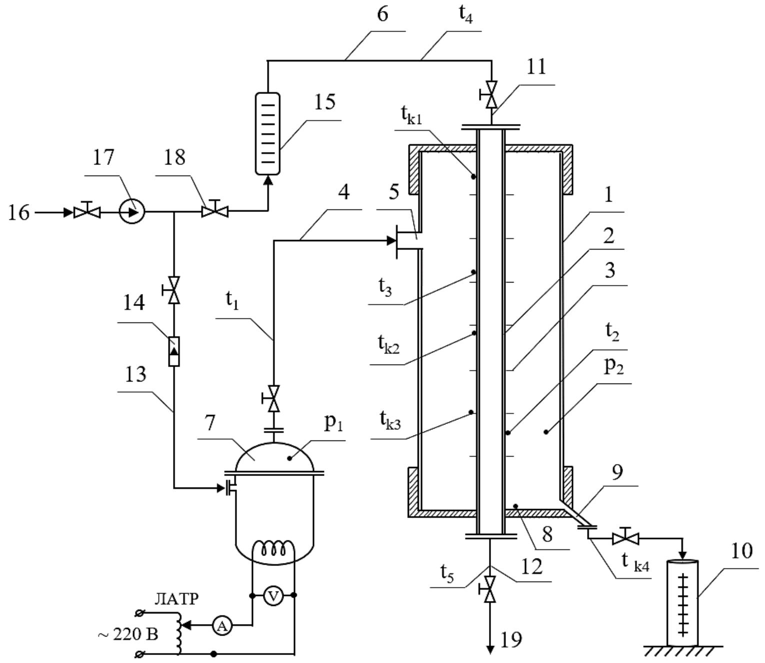

Fig. 1. Schematic diagram of the experimental laboratory stand: 1 – cylindrical glass container, 2 – smooth copper tube, 3 – fins, 4 – steam tube, 5 – steam inlet, 6 – cold water, 7 – steam generator, 8 – condensate, 9 – condensate tube, 10 – condensate collector, 11 – water inlet, 12 – water outlet, 13 – steam generator water supply, 14, 15 – rotameters, 16 – water supply, 17 – water pump, 18 – valve, 19 – drainage, p1, p2 – differential pressure gauge (testo 510), t_1, t_2, t_3, t_4, t_{k1}, t_{k2}, t_{k3}, t_{k4} – temperature measurement points

The main element of the experimental setup is a glass bulb with a diameter of 56/64 mm, respectively, a smooth copper tube is installed vertically inside 2. Fins are installed on the surface of a smooth copper tube after a certain distance 3. The diameter of a smooth copper tube is 10/12 mm, the length of the working section is $\ell = 300$ mm. The steam generator 7, equipped with a laboratory autotransformer (LATR), with an electric power of 690 Watts, produces steam for a cylindrical flask, with the parameters set for experiments. Since cooling water is supplied to the vertical tube, condensate 8 forms on the surface of the tube, which flows down the pipe 9 and collects in the condensate collector 10. The cooling water flow rate is regulated by the valve 18.

All temperature values in the laboratory unit were measured with a DS18B20 electronic thermometer with a measurement accuracy of 0,01 ^{0}C. DS18B20 electronic thermometers are connected to an Arduino board, programmed with a C++ program. Every second, the Excel program automatically registers readings. The flow rate of cooling water and condensate is measured by rotameters 14 and 15, of the RS-5 brand.

In experiments, the parameters varied in the following ranges: G_{water} = 0,01133 ÷ 0,025 kg/s, D_{steam} = 0,0000833 ÷ 0,000115 kg/s, P = 0,05 ÷ 0,13 MPa. The cooling water velocity W_{water} = 0,14 ÷ 0,32 m/s, the Reynolds number for cooling water Re_{water} = 1500 ÷ 3300, the steam velocity W_{steam} = 0,07 ÷ 0,09 m/s, the Reynolds number for steam W_{steam} = 125 ÷ 170, the temperature t_{steam} = 94 ÷ 105 0C.
The geometric parameters of an edge with an improved surface (EIS) are given in Table 1 [22].

Table 1. Geometric parameters of a vertical tube with an edge with an improved surface

Geometric parameters	A	B	C	D	E	F	G
Distance between edges S_2, mm	150	100	50	43	25	20	16,6
Edge sheet thickness δ, мм	0,001	0,001	0,001	0,001	0,001	0,001	0,001
Radius of curvature of the edge end r, mm	3 – 4	3 – 4	3 – 4	3 – 4	3 – 4	3 – 4	3 – 4
The radius between the smooth tube and the fin φ, degree	30 - 35	30 - 35	30 - 35	30 - 35	30 - 35	30 - 35	30 - 35
Outer diameter of the EIS d_{EIS}, mm	18 – 22	18 – 22	18 – 22	18 – 22	18 – 22	18 – 22	18 – 22
Diameter of smooth tube d_{out}/d_{in}, mm	12/10	12/10	12/10	12/10	12/10	12/10	12/10
Tube Length, ℓ, mm	300	300	300	300	300	300	300
Forming EIS, α, mm	5-7	5-7	5-7	5-7	5-7	5-7	5-7
The distance between the base of the generatrix and the smooth tube, b, mm.	3 - 5	3 - 5	3 - 5	3 - 5	3 - 5	3 - 5	3 - 5
Smooth tube area, $f_0 = 10^{-4}$, м^2	1,13	1,13	1,13	1,13	1,13	1,13	1,13
EIS Square, $f_{EIS} = 10^{-4}$, m^2	4,396	8,792	21,98	28,4	48,4	61,54	79,9
The total area of the vertical tube with EIS, $f = f_{EIS} + f_0$, m^2	0,0117	0,0121	0,0139	0,015	0,0164	0,0181	0,02
Finning ratio f / f_0	1,04	1,07	1,23	1,34	1,45	1,6	1,76

Boundary conditions have been established for various tubes used in experiments. The steam velocity at the entrance to the experimental flask W_{steam} = 0,07 ÷ 0,09 m/s and the corresponding values of the Reynolds number for the steam W_{steam} = 125 ÷ 170 are determined. The power of the steam generator increased to Q = 300 ÷ 630 watts.

3. Results and Discussion

Some generalized results of experimental studies are shown in Fig. 2 and 3. From Fig. 2 it can be seen that with an increase in the thickness of the condensate film δ along the length of the tube, the heat transfer coefficient α decreases. The intersection point of the condensate film thickness and the heat transfer coefficient can be taken as the most effective parameters. Analysis of a series of experiments has shown that the effective values of the parameters that intensify the thermal processes adopted for research vary in the following intervals:

- the distance between the edges with an improved surface, S_2 = 0,05 m;
- film thickness, δ = 0,1 – 0,11 mm;
- heat transfer coefficient, α = 10583÷6640 Wt / (m^2 · ^{0}C).

Based on the graphs shown in Fig. 2, the empirical equation of the change in the thickness of the condensate film δ along the length of the tube is obtained by the least squares method:

$$\delta = 0{,}028118 \ln(\ell) + 0{,}19028 \tag{1}$$

According to the above method, an empirical equation of the change in the heat transfer coefficient α along the length of the tube is obtained:

$$\alpha = -\,2006{,}2676 \ln(\ell) + 1194{,}157 \tag{2}$$

The average relative error of equations (1) and (2) is 3.7%. According to the Fisher criterion, the adequacy of the results of calculations based on empirical equations and corresponding experimental data was assessed. For (1) equation, calculated $Fr = 5.0821$, tabular $F_t = 7.71$, for equation (2) – calculated $F_r = 5.0821$, tabular $F_t = 7.71$, i.e. with $F_r < F_t$, the probability of reliability is adequate with an accuracy of 95%.

The change in the condensate output on a smooth tube, a tube with fins in the form of a truncated cone and a tube with fins with an improved surface is shown in Fig. 3., where it can be seen that under the same experimental conditions, the condensate output on the proposed vertical tubes with an improved fin surface is greater.

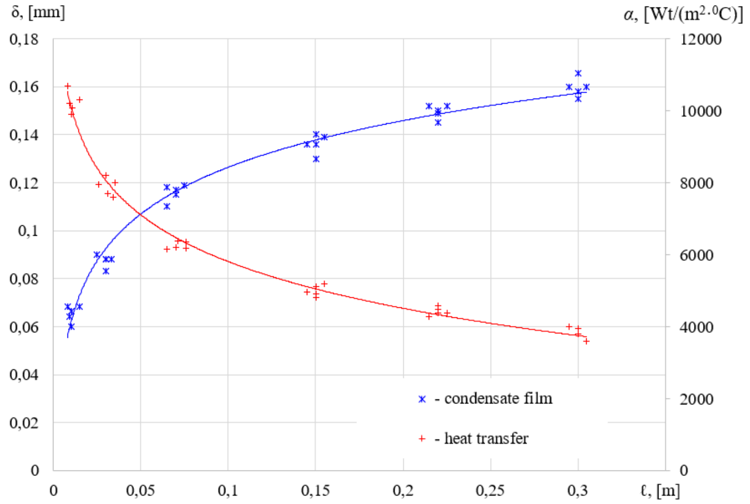

Fig. 2. Change in the thickness of the condensate film δ and the heat transfer coefficient α along the length of the tube

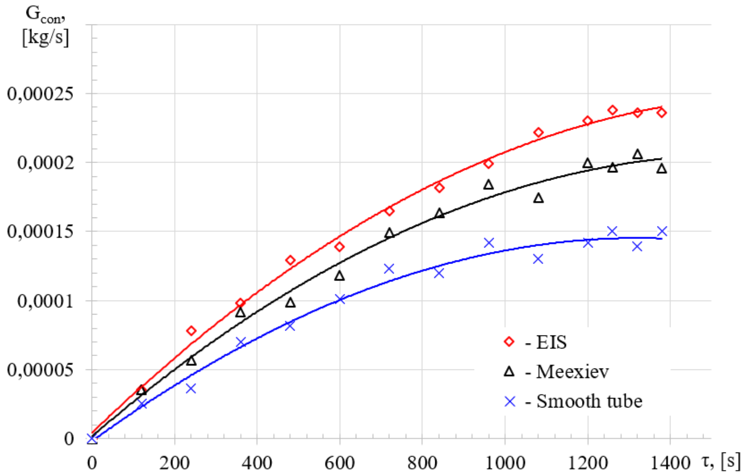

Fig. 3. Change of condensate output by time

4. Conclusions

Thus, based on the results of the experiments, it was determined that the average value of the heat transfer coefficient on smooth tubes is equal to 7258 Wt / ($m^2 \cdot {}^0C$), and for vertical tubes with an improved fin surface 8911 Wt / ($m^2 \cdot {}^0C$), that is, the heat transfer efficiency compared to a smooth tube is 23% greater. The condensate output of a relatively smooth pipe is 57% higher, and with respect to surfaces in the form of a truncated cone, proposed by Mikheev and Mikheeva, is 27% higher.

References

1. L. Eshkuvatov, M. Ruzinazarov, Methodology for conduction and calculation of the results of an experimental study for condensation of vapors on vertical tubes with specially profiled ribs, *International Journal of Advanced Research in Science Engineering and Technology* **9**, 20032-20037 (2022)

2. L. Eshkuvatov, R. Babakhodjaev, N. Tashbaev, Experimental study of the influence of the geometric structure of ribbing on a vertical tube on the heat transfer coefficient, *AIP Conf. Proc.* **2552**, 030021 (2023)
3. L.M. Eshkuvatov, N.T. Tashbayev, R.P. Babakhodjaev, Analysis of the current state of the efficiency of water vapor condensation on the surfaces of a vertical tube and development of an experimental stand, *Problems of Energy and Resource Conservation* **2**, 94–101 (2021)
4. L.M. Eshkuvatov, R.P. Babakhodjaev, N.T. Tashbayev, Analysis of experimental data processing methods for steam condensation on vertical pipes, International Conference on Energy and Resource Conservation: New research, Technologies and Innovative Approaches, KIEI (2021)
5. L.M. Eshkuvatov, R.P. Babakhodzhaev, Experimental setup for the study of steam condensation process in shell-and-tube heat exchangers, V All-Russian Scientific and Practical Conference on Energy and Energy Conservation: Theory and Practice, GTU, Kuzbass (2020)
6. L.M. Eshkuvatov, R.P. Babakhodjayev, N.T. Tashbayev, Study of steam condensation on vertical tubes of a heat exchanger and processing of the results, Technical science and innovation: TSTU, Tashkent (2021)
7. L.M. Eshkuvatov, Experimental study of steam condensation on vertical finned pipes, *Problems of Energy and Resource Conservation* **4**, 148-153 (2021)
8. I.A. Popov, H.M. Makhyanov, V.M. Gureev, Physical foundations and industrial application of heat exchange intensification: Heat exchange intensification, Center of Innovative Technologies, Kazan (2009)
9. S.L. Chen, F.M. Gerner, C.L. Tien, General film condensation correlations, *Exp. Heat Transfer* **1** 93–107, (1987)
10. L.M. Eshkuvatov, Increasing the efficiency of heat transfer in evaporators of the canning industry, International Conference on Problems and Prospects of Innovative Techniques and Technologies in the Agrarian-food Sector, Tashkent State Technical University, Tashkent (2020)
11. M. Kubín, J. Hirš, J. Plášek, Experimental analysis of steam condensation in vertical tube with small diameter, *Int. J. Heat Mass Transfer* **94**, 403-410 (2016)
12. L.M. Eshkuvatov, Influence of ribbing on increasing the efficiency of heat transfer in evaporators, International Conference on Trends and Prospects for the Development of Science and Education in the Context of Globalization, Pereyaslav (2020)
13. W. Roetzel, Laminar film condensation in tubes; calculation of local film resistance and local adiabatic mixing temperature, *Int. J. Heat Mass Transfer* **16**, 2297–2304 (1973)
14. R.A. Seban, J.A. Hodgson, Laminar film condensation in a tube with upward vapor flow, *Int. J. Heat Mass Transfer* **25**, 1291–1300 (1982)
15. S.L. Chen, F.M. Gerner, C.L. Tien, General film condensation correlations, *Exp. Heat Transfer* **1** 93–107 (1987)
16. L.M. Eshkuvatov, R.P. Babakhodjaev, N.T. Tashbayev, Physico-mathematical model of the steam condensation process in a vertical pipe with an improved fin surface, *Problems of energy and Resource Saving* **2**, 88-94 (2023)
17. Y. Liao, S. Guentay, D. Suckow, A. Dehbi, Reflux condensation of flowing vapor and non-condensable gases counter-current to laminar liquid film in a vertical tube, *Nuclear Eng. Des.* **239**, 2409–2416 (2009)
18. R. Babakhodjaev, D. Pulatova, J. Mirzaev, Z. Kurbanbaeva, Aerodynamics of the solid particle in the ascending stream of the intensified fluidized bed, *AIP Conf. Proc.* **2552**, 050025 (2023)
19. R. Babakhodjaev, N. Tashbaev, J. Mirzaev, A. Karimov, Study of elementary composition and structural characteristics of high-ash brown coal of angren deposit, *E3S Web of Conferences* **216**, 01122 (2020)
20. R.P. Babakhodjaev, D.A. Mirzaev, Numerical investigation of hydrodynamic processes in combustion chamber with an intensified fluidized bed, *Journal of Physics: Conference Series* **1683**, 022025 (2020)
21. R. Babakhodjaev, N. Tashbaev, D. Mirzaev, Use of kinetic flow energy liquids for vibration of local turbulizers in pipe heat exchangers, *E3S Web of Conf.* **216**, 01081 (2020)
22. L.M. Eshkuvatov, R.P. Babakhodjaev, B.R. Ismailov, N.T. Tashbaev, X.B. Ismailov, J.A. Mirzaev, X.A. Kuchinov, M. Kurbanbaeva, Finned tube, RepUz. Intellectual property agency, Patent for utility model FAP 02024, 27.06.2022.