

Investigation of the effect of pressure increasing in condensing heat-exchanger

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Abstract. The effect of pressure increase was observed in steam condensation in the intermediate coolers of multistage steam ejector. Steam pressure increase for ejector cooler amounts up to 1.5 kPa in the first ejector stage, 5 kPa in the second and 7 kPa in the third one. Pressure ratios are equal to 2.0, 1.3 and 1.1 respectively. As a rule steam velocities at the cooler inlets do not exceed 40...100 m/s and are subsonic in all regimes.

The report presents a computational model that describes the effect of pressure increase in the cooler. The steam entering the heat exchanger tears the drops from the condensate film flowing down vertical tubes. At the inlet of heat exchanger the steam flow capturing condensate droplets forms a steam-water mixture in which the sound velocity is significantly reduced. If the flow rate of steam-water mixture in heat exchanger is greater than the sound velocity, there occurs a pressure shock in the wet steam.

On the basis of the equations of mass, momentum and energy conservation the authors derived the expressions for calculation of steam flow dryness degree before and after the shock. The model assumes that droplet velocity is close to the velocity of the steam phase (slipping is absent); drops do not come into thermal interaction with the steam phase; liquid phase specific volume compared to the volume of steam is neglected; pressure shock is calculated taking into account the gas-dynamic flow resistance of the tube bundle. It is also assumed that the temperature of steam after the shock is equal to the saturation temperature.

The calculations have shown that the rise of steam pressure and temperature in the shock results in dryness degree increase. For calculated flow parameters the velocity value before the shock is greater than the sound velocity. Thus, on the basis of generally accepted physics knowledge the computational model has been formulated for the effect of steam pressure rise in the condensing heat exchanger.

The effect of pressure increasing during the steam condensing into the intercoolers was found out at the experimental researches of multistage steam-jet ejector with external intercoolers. A scheme of a three-staged ejector is presented on figure 1.



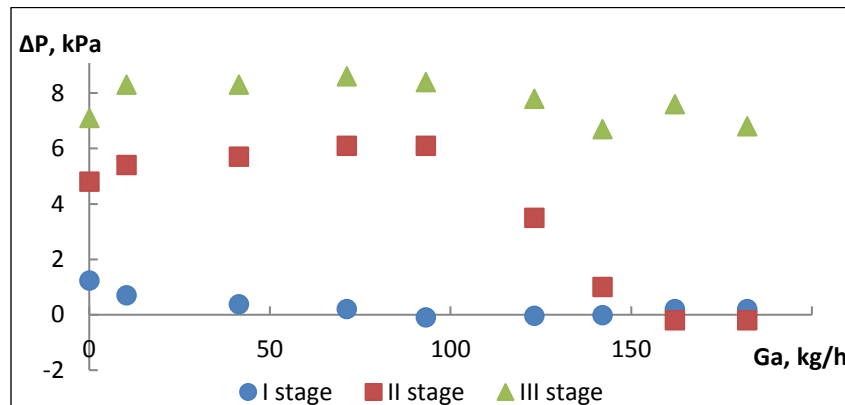


Figure 2. Steam (air-steam mixture) pressures difference of intercooler inlet and outlet

For the first stage, the air-steam mixture pressure at the intercooler inlet is lower for 2,7 kPa (maximum), than at the outlet ($\Delta P_{\max} = 2.7$ kPa), for the second stage - $\Delta P_{\max} = 6.9$ kPa, for the third stage - $\Delta P_{\max} = 10.9$ kPa.

At the figure 3 the pressure differences (pressure drop $\delta P = P_{\text{outlet}} / P_{\text{inlet}}$) in the first, second and third stage intercoolers for one ejector working mode are presented. The pressure drop in the first intercooler reaches $\delta P = 2.08$; in the second intercooler - $\delta P = 1.28$; in the third intercooler is in the range of $\delta P = 1.07 \dots 1.12$.

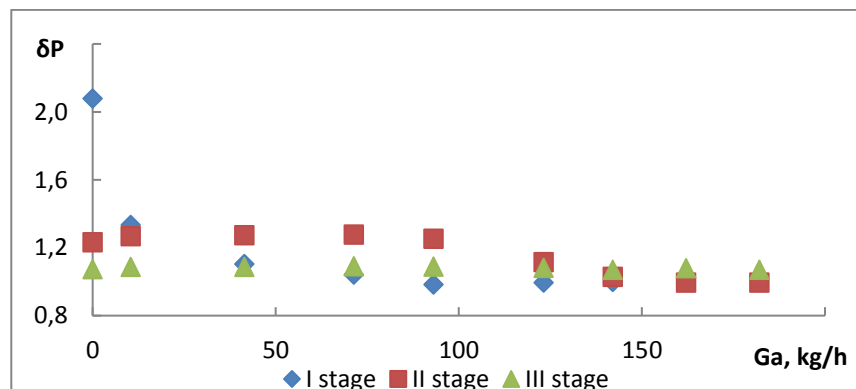


Figure 3. Pressure drop in the intercooler

For the explanation of the effect, a number of hypothesis are considered: a condensation drop; a thermal drop; a diffuser effect, consisted in geometric, thermal and flow rate factors simultaneously; a wet steam pressure drop [0,0]. A condensation drop in the stream is implemented in the presence of high supersonic velocities ($M \gg 1$). The steam velocities at the diffuser outlet (intercooler inlet) reaches, as usual, 60-100 m/s, except of the mode without the secondary stream (when an air flow rate $G=0$ kg/s). In this mode, the pressure in diffuser outlet had reached 1,4 kPa (in the injection chamber $P_1=0,7$ kPa) and the stream velocities at the diffuser outlet - about 450 m/s. However, at all the modes, the velocity of the stream in the diffuser outlet is subsonic. For the thermal drop implementation in following experimental conditions (a pressure drop), the temperature decreasing for a steam (an air-steam mixture) should be about 250-300 K. Experimental values of a superheated steam temperatures at the diffuser outlet were exceeding the value of steam saturation temperature for 80-100 K. At last, the integrated diffuser effect leads to the steam pressure increasing. However, at following experimental parameters, the pressure increasing is several times lower, than it was fixed in

the experiment. Consuming all said above, the implementation of thermal or condensation drops, or diffuser effect for the experimental conditions – is impossible.

For the explanation of the fixed effect, the most suitable hypothesis is the pressure drop in the wet steam. Probably, the steam (air-steam mixture), getting into the heat-exchanger, breaks the condensate film, flowing down from the vertical tubes. At the same time, the steam catches and breaks condensate drops and jets, which are flowing down from the highest intermediate partition. At the heat-exchanger inlet, the gas-steam-water mixture (mist) is appeared. It is known [1], that the sonic speed in the wet steam is decreased extremely. The stream becomes supersonic in the intercooler inlet and a pressure drop in the wet steam appears. So, when the wetness calculation at the intercooler inlet show the Mach number $M > 1,0$, it means that the hypothesis of the pressure drop inside the intercooler is correct for the explanation of the fixed effect.

For a mathematic formulation of the process describing model, we are going to make several assumptions and additions, basing on the parameters measuring results:

The air-steam mixture at the heat-exchanger inlet is superheated, relating to the saturation temperature, which is devoted to the mixture pressure. In the heat-exchanger inlet, the mixture is cooled and a part of moisture is evaporated.

The temperatures upstream and downstream the drop are corresponding to the saturation temperatures at the mixture pressures.

Drops impulse velocities are close to the gas phase velocity (sliding is absent).

Liquid phase specific volume is neglected comparing to the gas specific volume.

The Clapeyron equation is applicable for the gas phase.

The pressure drop is calculated taking into account the pipe bunch gas-dynamic resistance. It is connected with the fact, that the mixture pressure is measured downstream the intercooler, when the pressure drop takes place in the intercooler entrance (according to the authors assumption).

The mass, momentum and energy conservation equations are written down, using [1]:

$$\frac{w_2}{w_1} = \frac{\beta_{sa2} \cdot T_2 \cdot P_1}{\beta_{sa1} \cdot T_1 \cdot P_2} \quad (1)$$

$$P_2 - P_1 = \frac{\rho_{sa1} \cdot w_1}{\beta_{sa1}} \cdot (w_1 - w_2) \quad (2)$$

$$r_1 \cdot \beta_{s1} + h_{cs1} \cdot \beta_{cs1} + h_{a1} \cdot \beta_{a1} + w_1^2 / 2 = r_2 \cdot \beta_{s2} + h_{cs2} \cdot \beta_{cs2} + h_{a2} \cdot \beta_{a2} + w_2^2 / 2 \quad (3)$$

Into equations (1) – (3), using indexes “1, 2” the environment parameters upstream and downstream the drop are designated; «c, a, s» – parameters of condensate (moisture), air and steam; double indexes are related to double-component mixture: «sa» – steam and air (gas component), «cs» – condensate and steam. The variables indexes are: w – velocity; T, P – temperature, pressure; ρ – component density; r, h – phase transition heat, heat content; β – component weight quota.

In the equations (1) – (3), the unknown variables for provided experiments are the moisture quota upstream and downstream the drop, and also the stream velocity downstream the drop. The equations set is solved by the iteration method.

The sonic speed in the gas-steam-water mixture is determined by equation (3).

$$\frac{1}{a_{mix}^2} = \rho_{mix} \cdot \left[\frac{v_a}{\rho_a \cdot a_a^2} + \frac{v_{sc}}{\rho_{sc} \cdot a_{sc}^2} \right], \quad (4)$$

where a – sonic speed; ρ – density; v – component volume fraction; indexes: mix, a, sc – mixture, air, steam-condensate; $\rho_{mix} = \rho_a \cdot v_a + \rho_{sc} \cdot v_{sc}$.

The sonic speed in the wet steam was determined by the diagram [1], figure 4.

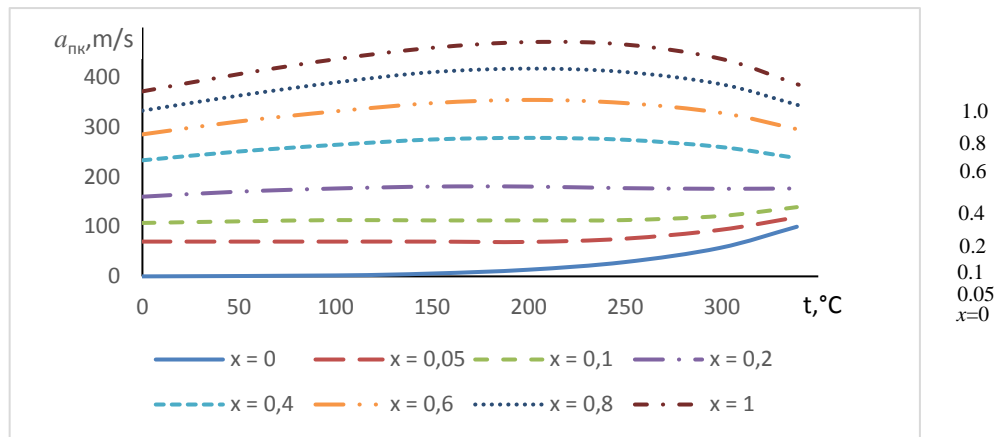


Figure 4. The dependence of the sonic speed in the double-phase environment ($a_{ПК}$) from the steam temperature for various wetness of water steam mixture (x) [0]

The results of the Mach number calculation upstream and downstream the pressure drop are presented at figure 5. As it is clear from the figure, for all the intercoolers, the Mach number upstream the pressure drop is $M > 1$. This means, that the hypothesis, explaining the pressure drop in the intercoolers is correct.

According to the solutions of the equations (1) – (3), steam wetness for the first stage is $x < 0.75$ at various operating moods of the ejector. For the second and the third stages it is $x < 0.09$. The steam wetness doesn't change considerably with the drop. For the wet steam formation, in compliance with (1) – (3) equations, it is required 10% of moisture, which is located on the intercooler tubes as the condensate drops.

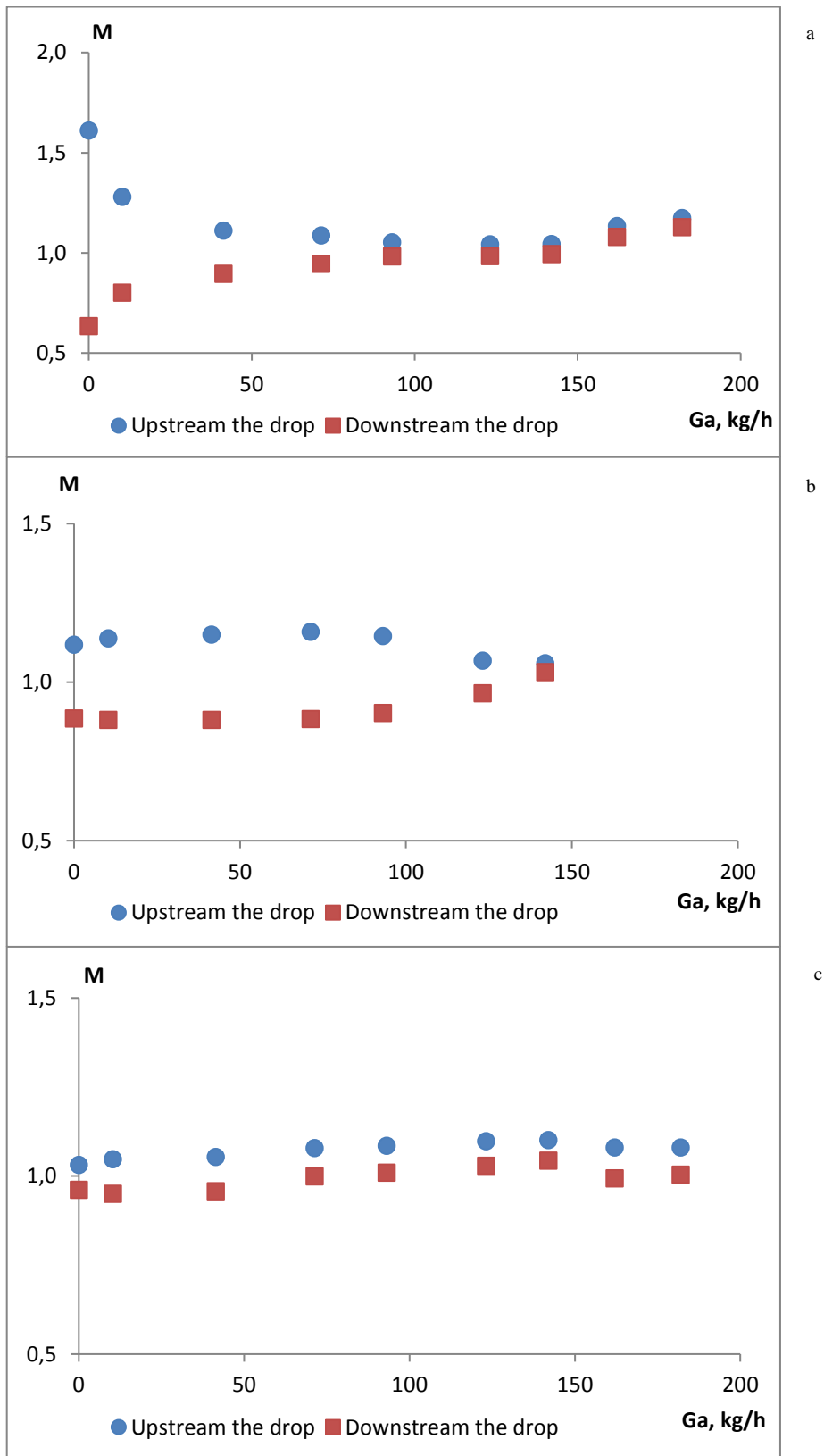


Figure 5. The Mach number upstream and downstream of the pressure drop
 a. – first stage; b – second stage; c. – third stage

Conclusion

The effect of the steam (air-steam mixture) pressure increasing in the intercoolers of the tree-staged steam-driven ejector is fixed during the experimental research. The pressure drop in the intercoolers reaches 2,7 kPa for the first stage, 6,9 kPa – for the second stage, 10,9 kPa – for the third stage.

For the explanation of the fixed effect, a hypothesis is suggested. At the heat-exchanger inlet, the air-steam mixture stream breaks the drops of the condensate, which is flowing down from the tubes, and also divides the jets of the, flowing from the lowest intermediate partition, condensate into drops. At the heat-exchanger inlet, the gas-steam-water mixture (mist) is appeared. As the sonic speed in the wet steam is decreased extremely, comparing to a single-phase stream, at the heat-exchanger inlet, the stream becomes supersonic. A pressure drop appears.

Basing on the formulated hypothesis and also several assumptions, equations of the mass, momentum and energy balances are made. As a result of set of equations solving, it is determined that the mixture velocity upstream the drop is supersonic for experimentally gotten values of the gas-water steam mixture upstream the heat-exchanger.

To authors mind, suggested hypothesis of the formation of double-phase double-component mixture in the heat-exchanger inlet explains fixed effect of the pressure drop in the multistage steam-driven ejector intercoolers correctly.

Results, provided in the paper, cause the necessity of the multistage steam-driven ejectors design methodic reviewing. An additional investigation of such apparatuses is necessary.

References

- [1] M.E. Deych. Gas dynamics of two-phase environments / M.E. Deych, G.A. Filippov // M: Energia, 1981, 423 p.
- [2] Samoylovich G.S. Gas dynamics: Textbook for Universities for speciality “Turbine design” // 2d edition, M: Mashinostroeniye, 1990, 384 p
- [3] Ahuja V. Simulations of cavitating flows using hybrid unstructured meshes / V. Ahuja, Hosangadi A., Arunajatesan S. // Journal of fluids engineering. 2001, vol. 123. PP. 331–340.