Numerical Modeling of the Effect of Inlet Temperature and Pressure on Steam Condensation and Entropy Generation in High-Pressure Separator

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ABSTRACT

The gas-liquid supersonic separator is a convergent-divergent nozzle in which condensation and phase change at speeds higher than sound are the characteristics of this device. The fluid flow, mass, and heat transfer in supersonic separators are not understood well due to the complicated interaction of the supersonic flow and phase change. In this research, the virial gas equation of state and a mathematical model have been used to accurately predict spontaneous condensation using nucleation and droplet growth theories. The droplet average radius and pressure distribution obtained from the numerical model are well consistent with the experimental data. The results showed that with a 3.5% decrease in inlet temperature at a constant pressure, the average radius of the outlet droplets increased by more than 40%. Also, with about a 40% increase in inlet pressure at a constant temperature, the maximum liquid mass fraction increased by more than 90%. Therefore, low temperature and high pressure at the inlet are necessary to improve the separation efficiency. Also, the lowest entropy generation rate due to temperature changes is related to the highest pressure and the lowest temperature, and the lowest entropy generation rate due to pressure changes is related to the lowest temperature and pressure. The Bejan number calculation showed that irreversibility is affected by the effects of fluid friction compared to heat transfer.

KEYWORDS

Supersonic separator, Two-phase flow, Spontaneous condensation, Entropy generation, The Bejan number.

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1. **Introduction**

Considering the increasing use of natural gas as a source of energy production, as well as the discovery and emergence of new gas sources, providing as many new related technologies as possible is introduced as a basic need for the development of this industry. In the gas refining and transmission sector, natural gas dehumidification is one of the prerequisites. The raw gas extracted from the wells, has some impurities, including water vapor, which reduce the calorific value of the gas; If this water vapor condenses inside gas transmission pipelines, it can cause major problems including corrosion, reduced transmission efficiency, and hydrate formation. The supersonic separator, which is a converging-diverging nozzle, is an advanced separation technology focusing on water vapor removal [1, 2].

Since most of the previous research has not used a suitable model for simulating and observing the phenomenon of condensation and the formation of liquid particles, the innovations of the present research are: (1) Considering the ambiguities related to the correct method of mathematical modeling, a suitable model is used to simulate the condensation phenomenon of water vapor particles and to evaluate the fluid flow inside the supersonic separator. (2) Considering that the numerical simulation results depend on different nucleation theories and different droplet growth models, the appropriate theory and model are used to minimize the error between numerical modeling results and experimental data. (3) Also, investigating entropy generation (due to temperature and pressure changes) in the supersonic separator is another innovation that has not been discussed in the past.

2. **Methodology**

For the condensation of water vapor inside the nozzle, the fluid flow behavior is described by partial differential equations as follows [3].

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = S_m \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + S_{u_i} \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_j}(\rho u_j E + u_j P) =$$

$$\frac{\partial}{\partial x_j}(\lambda_{eff}\frac{\partial T}{\partial x_j} + u_i \tau_{ij}) + S_h \qquad (3)$$

Mass conservation equation for liquid phase [4]:

$$\frac{\partial}{\partial t}(\rho y_d) + \frac{\partial}{\partial x_j}(\rho u_j y_d) = S_y \qquad (4)$$

To accurately describe heat and mass transfer, another transfer equation that specifies the number of liquid droplets per unit mass (N_d) is written as [4]:

$$\frac{\partial}{\partial t}(\rho N_d) + \frac{\partial}{\partial x_j}(\rho u_j N_d) = S_N \qquad (5)$$

Together, these equations form a closed system of equations that allow the calculation of the wet steam flow field.

The volumetric rate of local entropy generation due to temperature changes is expressed in equation (6) [5].

$$\dot{S}'''_{gen,\Delta T} = \frac{\lambda_{eff}}{T^2}(\nabla T)^2 = \frac{\lambda_{eff}}{T^2}\left[(\frac{\partial T}{\partial x})^2 + (\frac{\partial T}{\partial y})^2\right] \qquad (6)$$

Also, the volumetric rate of local entropy generation due to pressure changes is defined by equation (7) [5].

$$\dot{S}'''_{gen,\Delta P} = \frac{\mu_{eff}}{T}\varphi^2 \qquad (7)$$

The Bejan number (Be), which expresses the ratio of the entropy generation rate due to temperature changes ($\dot{S}_{gen,\Delta T}$) to the total entropy generation rate, is calculated through equation (8) [6, 7].

$$Be = \frac{\dot{S}_{gen,\Delta T}}{\dot{S}_{gen,\Delta T} + \dot{S}_{gen,\Delta P}} \qquad (8)$$

The equation of state formulated by Yang [8], which is used in the present research, is expressed by the following relationship:

$$P = \rho_v R_v T(1 + B\rho_v + C\rho_v^2) \qquad (9)$$

3. **Results and Discussion**

For validation, the experimental data of the Headback nozzle [9] is used; The geometry and dimensions of this nozzle are given in Figure 1.

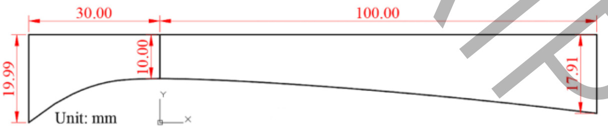

Figure 1. Nozzle geometry and dimensions

Figure 2 shows the comparison between the pressure distribution and the droplet average radius results obtained from the numerical simulation and the experimental data along the geometry axis. The flow conditions at the nozzle inlet are presented in this Figure. As can be seen, the predictions of the droplet average radius and the location and strength of the condensation shock are in good agreement with the experimental data. Therefore, these results confirm the numerical model and show that the simulation method used in this research can be performed for the condensation of single-component supersonic flows in nozzles.

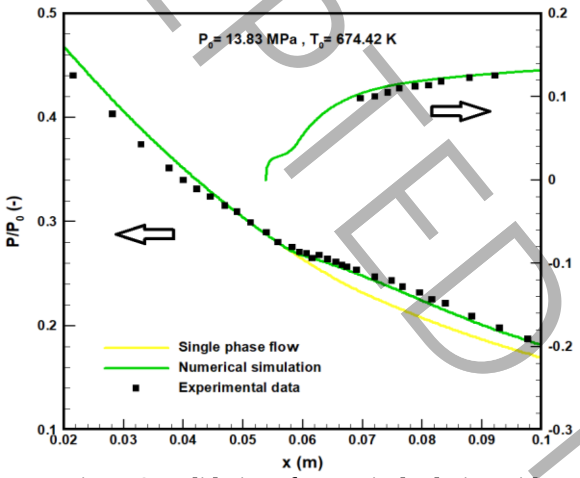

Figure 2. Validation of numerical solution with experimental data [9]

According to the geometry, the nature of the flow, and the adiabatic boundary condition on the nozzle wall, as expected, the entropy generation rate due to temperature changes versus pressure changes is negligible ($\dot{S}_{gen,\Delta P} \gg \dot{S}_{gen,\Delta T}$); Therefore, the major contribution to the total entropy generation rate is due to pressure changes. According to Table 1, with the increase in temperature at a constant pressure of 13.83 MPa, the rate of entropy generation due to both temperature and pressure changes has increased; By increasing the pressure at a constant temperature of 674.42 K, the rate of entropy generation due to temperature changes has decreased and the rate of entropy generation due to pressure changes has increased. Therefore, the lowest amount of entropy generation rate due to temperature changes is related to the highest pressure and the lowest temperature, and the lowest amount of entropy generation rate due to pressure changes is related to the lowest temperature and pressure. Also, by increasing the temperature from 662.45 K to 686.43 K at a constant pressure of 13.83 MPa, the total entropy generation rate increased by 9.75%; By increasing the pressure from 9.83 MPa to 13.83 MPa at a constant temperature of 674.42 K, the total entropy generation rate increased by 15.95%.

Table 1. Entropy generation rate

Row	$P_0\,(MPa)$	$T_0\,(K)$	$\dot{S}_{gen,\Delta P}\,(W/K)$	$\dot{S}_{gen,\Delta T}\,(W/K)$
1	9.83	674.42	640.254	101.654
2	11.83	674.42	716.858	97.693
3	13.83	662.45	749.721	64.345
4	13.83	674.42	776.708	83.499
5	13.83	686.43	793.461	100.007

4. Conclusions

By increasing the inlet pressure at a constant temperature or decreasing the inlet temperature at a constant pressure, it was observed that (1) the steam reaches the supersaturated/supercooled state faster, (2) the nucleation process happened faster and it is easier to reach condensation, (3) the liquid droplets formed faster, will have more opportunity to grow and will have a larger radius, (4) with the faster formation of the liquid phase and the increase in the droplet average radius, the mass fraction of the liquid will increase.

5. References

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