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Numerical study of primary steam superheating effects on steam ejector flow and its pumping performance

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A B S T R A C T

The effects of primary steam superheating on steam condensation in nozzle and the performance of steam ejector were investigated using CFD (computational fluid dynamics) method. Using a wet steam model being proposed in our previous study, simulations based on the primary steam with five superheated levels were performed, and the results demonstrate the superheating operation of the primary steam weakens the spontaneous condensation intensity and postpones its occurrence within the nozzle vicinity. Due to the droplets nucleation refinement for the condensation of superheated steam, the mixing process between the primary and the secondary fluids is improved. Consequently, a higher entrainment ratio is achieved. However, the superheating operation may not exceed 20 K, as its contribution on entrainment ratio improvement is not as significant as 0 K–20 K superheating, and too much superheating will requires more energy as input, which is not a practical solution to further improve the steam ejector pumping performance.

1. Introduction

Steam ejector is widely used in chemistry, petroleum, metallurgy, refrigeration, and food industry to generate a vacuum environment for special purposes. A typical steam ejector includes four parts as shown in Fig. 1a: Laval nozzle, mixing chamber, throat and diffuser [1]. Simplified pressure and velocity distributions along the centerline of the steam ejector are depicted by Fig. 1b. First, the primary fluid, which is steam with high pressure (0.3–1.6 MPa) is accelerated to supersonic speed through the converging-diverging Laval nozzle. Then, a low pressure region is established downstream of the nozzle outlet. Driving by the pressure difference, the secondary fluid is entrained into the mixing chamber and accelerated to supersonic speed by the primary fluid. After a mixing process involving energy and momentum exchange between these two types of fluid, a normal shock wave occurs in the throat, and the velocity of the mixing fluid suddenly drops down to a subsonic level. Finally, the mixed fluid is exhausted to the next stage by the diffuser.

Entrainment ratio E_m is a widely accepted indicator to assess the pumping performance of a steam ejector, and it equals to the ratio of mass flow rate between the secondary fluid and the primary fluid. Huang et al. [2] investigated the entrainment ratio variation regarding on different operating back pressure values, and they divided the ejector operating status into three modes (Fig. 2): critical mode, subcritical mode and malfunction. When the back pressure P_b is below the critical back pressure P_b^*, the secondary flow is choked in the mixing chamber, and the entrainment ratio E_m remains constant. However, once P_b is higher than P_b^*, the secondary flow becomes unchoked, and E_m begins to decrease rapidly. When P_b is greater than the reversing back pressure P_b^r, the high back pressure jeopardizes the ejector entrainment process, leading to a flow reverse in the mixing chamber. Therefore, the steam ejector should be operated within the critical mode to maintain a steady pumping performance. As a result, accurate prediction of E_m variation regarding on different back pressure settings and the determination of the critical pressure P_b^* play critical roles in theoretical analysis and engineering applications.

Due to the transonic flow nature, the complicated mixing flow in the steam ejector is difficult to be described by classical mathematical methods [2,3]. Alternatively, computational fluid dynamics (CFD) is a good choice as a research tool to investigate and predict the internal flow behavior for steam ejectors. Although steam ejectors have been extensively studied using different numerical approaches for decades, majority of them were based on the ideal gas assumption [4–9], while influences induced by the spontaneous condensation were not taken into account. This

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Nomenclature

B, C	virial coefficients (m^3/kg, m^6/kg^2)
C_p, C_{p0}	isobaric heat capacity, standard state heat capacity (J/(kg K))
E_m	entrainment ratio
h, h_0	specific enthalpy, standard state enthalpy (J/kg)
h_v	vapor specific enthalpy (J/kg)
I	nucleation rate (1/s)
K_B	Boltzmann constant (J/(mol K))
k	turbulent kinetic energy (m^2/s^2),
M	molecular mass (kg)
P	pressure (Pa)
P_b	back pressure (Pa)
M	molecular mass (kg)
P	pressure (Pa)
P_b^*	critical back pressure (Pa)
P_b^r	reversing back pressure (Pa)
q_c	evaporation coefficient
R	gas-law constant (J/(mol k))
$\bar{r}$	droplet average radius (m)
r^*	critical droplet radius (m)
S	super saturation ratio
s, s_0	specific entropy, standard state entropy (J/(kg mol K))
T	thermal temperature (K)
T_0	droplet temperature (K)
t	time (s)
u	velocity (m/s)
V_d	average droplet volume (m^3)
α_v	volume fraction
β	mass fraction
γ	specific heat capacities ratio
Γ	mass generation rate (kg/s)
ε	turbulent energy dissipation rate (m^2/s^3)
η	droplet number density ($1/m^3$)
θ	non-isothermal correction factor
μ, μ_t	dynamic viscosity, turbulent viscosity (Pa s)
ν	kinetic viscosity (m^2/s),
ρ, ρ_l, ρ_v	mixture density, liquid density, vapor density (kg/m^3)
σ	droplet surface tension (N/m)

simplification may contribute to some prediction uncertainties for the determination of the entrainment ratio and the critical pressure.

As a critical part of a steam ejector, the nozzle plays a key role in the acceleration of the primary fluid and the entrainment of the secondary fluid. Thus, the associated fluid thermodynamics characteristics occurring within the nozzle are theoretically examined (Fig. 3). Along with the acceleration of the primary fluid, the saturated assumed primary fluid expands from its stagnation pressure level A to its suction pressure level B along the isentropic expansion line AC, and intersects with the isobar line CB at point C. However, the real expansion process may follows line AC' when taking the nozzle efficiency and fraction loss into consideration. It should be noted that either of the steam status at point C or C′ is in its super-saturation state as the dryness value of these two points are below one. As the current steam pressure is fairly above its saturation pressure which is determined by its current temperature. In such a circumstance, a spontaneous condensation will occur, and our previous work [10] demonstrated its existence when the supersonic flow passes through the nozzle using a wet steam modeling approach, and the wet steam model also gave a close predication of E_m [11, 12].

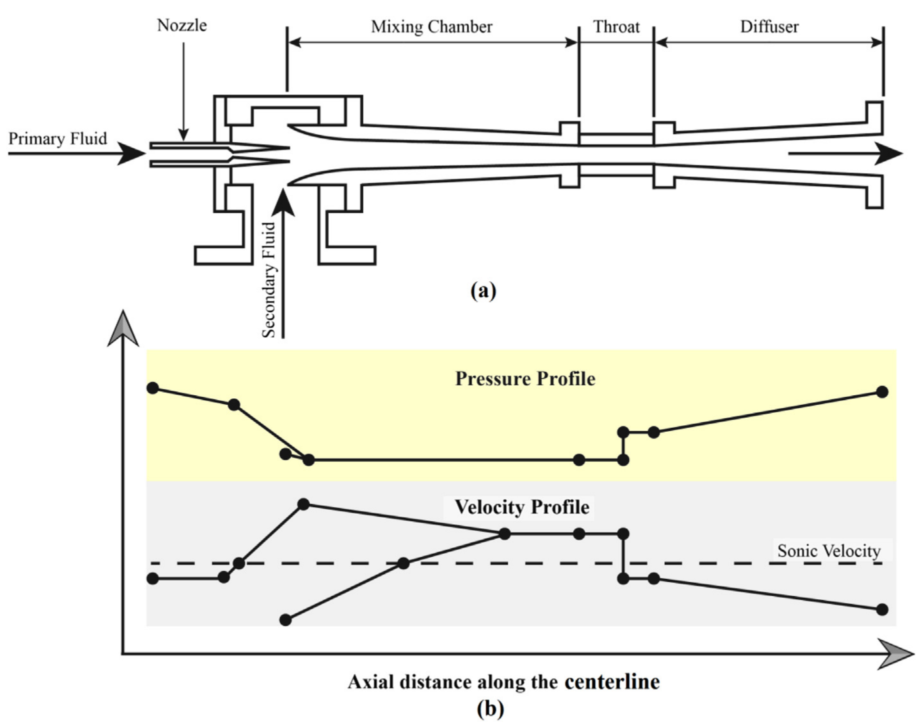

Fig. 1. Schematic diagram of a steam ejector: (a) geometry configuration (b) axial pressure and velocity profiles along the centerline.