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Wet steam flow energy analysis within thermo-compressors

Navid Sharifi [a], Masoud Boroomand [a,*], Ramin Kouhikamali [b]

[a] Department of Aerospace Engineering, Amirkabir University of Technology, Tehran, Iran
[b] Department of Mechanical Engineering, Faculty of engineering, University of Guilan, Rasht, Iran

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A B S T R A C T

Thermo-compressors are widely used in industries for steam compression through a thermal process. Common methods of thermo-compressors analysis are based on the hypothesis of considering steam as a perfect gas. In this study, the deviation of thermo-compressor performance at wet steam conditions from the performance under the ideal gas assumption has been investigated. Firstly, a numerical method has been implemented to evaluate the formation of droplets due to condensation in a convergent–divergent nozzle. The results have been validated using existing experimental data for single nozzles. Afterwards, the verified numerical scheme has been applied to internal flow of the thermo-compressor. The formation of droplets due to condensation effect and the resulting supersonic core in the thermo-compressor have been deeply investigated. Finally, the effect of wet steam assumption on the performance characteristics of thermo-compressors has been presented.

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1. Introduction

Multi Effect Distillation (MED) systems could be improved by adding vapor compression devices. The vapor compression process could be performed mechanically or thermally. The desalination packages are known as MED-MVC (MED with mechanical vapor compression) or MED-TVC (MED with thermal vapor compression). The main advantages of the TVC usage are the reuse of the compressed vapor that reduces the required amount of motive steam, low capital and construction costs and the simplicity of the steam compressor. Some methods were presented to improve the performance and the efficiency of simple distillation units without thermo-compressor those are based on the multiple condensation–evaporation cycles [1]. However, thermo-compressors are one of the most important parts of desalination systems in which considerable quantities of energy loss is occurred and thus, needed to be designed carefully [2]. Moreover, the simplicity of this device, with no moving parts, gives a forward step compared against the mechanical vapor compressor. It was shown that a single stage mechanical compressor was not feasible for compressing water vapor because of high capital cost and technically challenging compressor design and development [3].

Thermo-compressors compress large amounts of low-pressure steam through using the available pressurized steam as motive energy. The motive steam passed through a convergent–divergent nozzle of the thermo-compressor may be condensed at the exit section due to temperature decrease caused by supersonic conditions. The condensation phenomenon occurred in supersonic flow is studied deeply in “wet-steam” theory. Wet steam is typically considered as a multiphase mixture in which both vapor phase and liquid droplets exist. In this case, formation of liquid droplets due to pressure decline causes some complexities. Recent studies have been concentrated on the computation of such multiphase flows to determine the rate of droplets growth, condensation shock position, and energy losses in the last stages of steam turbines.

The theory of steam nucleation in converging–diverging nozzles has been studied for several decades, and originally was focused on one-dimensional flow analysis in Laval nozzles, because of the well suited geometry for experimental purposes. Moore et al. used light scattering method to experimentally obtain the pressure distribution along the centerline of convergent–divergent nozzles [4]. Furthermore, the order of magnitude of the droplets diameter was reported in their study. In order to establish a reasonable numerical model, Jackson et al. [5] developed a general equation set for multidimensional, time variant, inviscid flow of a condensing vapor which is capable of predicting the effects of relative motion between the primary gas phase and the suspended liquid droplets. The complete set of conservation equations for gas-droplet

* Corresponding author. Tel.: +98 21 64543280; fax: +98 21 66959020.
E-mail address: boromand@aut.ac.ir (M. Boroomand).

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multiphase flow was further introduced by Young [6]. These governing equations were frequently used in recent studies of wet steam flow. To assist in this objective a number of researchers developed wet steam theories to be used in understanding this phenomenon. The nucleation rate and droplets growth were investigated thoroughly for both steady and unsteady conditions [7,8]. Besides, two-dimensional calculations were developed for considering the real flow behavior in turbine cascades [9–11]. In order to explicitly track the particle motion, the Lagrangian approach was established based on inviscid time marching schemes. The Eulerian–Lagrangian approach was further introduced, whereby conservation equations for the mixture flow were solved in the Eulerian model, and the Lagrangian approach was used for calculating the specific properties of liquid droplets [12,13]. Compared with the Eulerian approach [14], this method had some advantages which were described in detail by White et al. [15].

Thermo-compressors are prevalently studied as a conventional supersonic ejector. The early ejector studies conducted by Keenan (1946), Fabri (1958), Taylor (1969), and Dutton (1976) were focused on the development of ejector design techniques [16–19]. Further studies developed design methods based on fundamental relations of gas dynamics under the assumptions of isentropic processes, inviscid flow and one-dimensional modeling [20–22]. More recently, computational fluid dynamics (CFD) has been extensively used for capturing the internal phenomena of ejectors [23–27]. However, these studies have generally used air [28–31] or other gases (for example, refrigerants [32–35]) as working fluid and a few of them focused on steam ejectors. Moreover, the ideal gas assumption for the vapor equation of state was used in the latter studies due to its simplicity [36–39]. Furthermore, some modifications were implemented based on the ideal steam hypothesis in order to improve the geometry of thermo-compressors through using the CFD methods [40–43].

The review of the previous works showed that numerous studies were conducted on numerical simulations of flow inside steam ejectors and thermo-compressors. However, according to the authors' knowledge, all the above studies considered the flow as a dry gas and there is no specific study of flow behavior under the assumption of wet steam condition. The present investigation is devoted to study the effects of wet steam phenomenon on the fluid flow and heat transfer within thermo-compressors.

In the current study, a numerical method of predicting flow properties through using wet steam theory is introduced. The assumption of homogeneously nucleating steam is firstly validated through using the experimental data from Moore et al. [4] and then applied to the computational domain of the studied thermo-compressor. The influence of wetness conditions on the supersonic region of the internal flow is scrutinized and compared with that of the ideal steam assumption. Finally, the effects of homogenous steam condensation on the main characteristics of the thermo-compressor are investigated. From this point of view, the deviation of overall performance of the thermo-compressor from the ideal assumption is presented.

2. Model description

2.1. Thermo-compressor identification

A conventional thermo-compressor consists of four distinct parts as it can be observed in Fig. 1: Primary nozzle, mixing zone, constant area zone and the diffuser.

Motive steam is externally provided for the thermo-compressor and passes through a convergent–divergent nozzle (primary nozzle) for the purpose of accelerating to supersonic level. This phenomenon causes a major pressure drop due to high supersonic flow at the downstream of the nozzle exit plane. The low pressure region created locally is able to entrain the surrounding flow and drive it in the same direction. This entrained stream is often called "secondary flow" in contrast with "primary flow" which is related to the motive steam. Flow passing through the converging duct is choked in the constant area section (i.e. the thermo-compressor throat). The high pressure region at the downstream of diffuser and decelerating of mixed stream through the flow pathway, cause a normal shock which is often taken place in the constant area section. After the shock occurrence, the pressure of mixed flow is raised up and exited from the diffuser with higher pressure.

Two characteristic parameters can be defined for the performance of a typical thermo-compressor. "entrainment ratio" (ER) is defined as the ratio of secondary mass flow rate to the primary one $\dot{m}_{\mathrm{suc}}/\dot{m}_{\mathrm{mot}}$, while "compression ratio" (CR) is defined as the ratio of discharge pressure to the suction pressure $p_{\mathrm{dis}}/p_{\mathrm{suc}}$.

2.2. Two-phase flow consideration

It is obvious when the steam pressure in the mixing chamber is suddenly reduced, the corresponding temperature is decreased and some droplets might be created due to sub-cooling effect. The droplets appeared in the vapor are very small particles (10^{-3}–10^{-4} μm) and supposed to be spheres which are growing several orders of magnitude in a very short period of time. This concept may not be covered just by simple assumption of steam as a perfect gas, because this hypothesis has no capability to predict the real gas properties in the temperature regions lower than saturation level. Therefore, the assumption of perfect gas equation of state (i.e. $P = \rho RT$) may not lead to proper results for such applications.

2.3. Wet steam theory

The flowing steam which undergoes expansion through the nozzle causes the formation of the minute embryos of liquid droplets in the vapor which are called "nuclei" and this phenomenon is called "nucleation". The distinct media which exist in the entire flow field consists of water vapor (gas phase), water droplets (liquid phase) and the mixture of two phases. Hence, in the following expressions, the subscripts g and l indicate the vapor and liquid phase properties, respectively. Moreover, parameters with no subscript indicate the mixture properties.

The classic theory of nucleation which was proposed by Volmer–Frenkel–Zeldovich is used herein to calculate the number of liquid particles [44,45].

$$J_{\mathrm{classic}} = \frac{q_c}{1+\eta}\left(\frac{2\sigma}{\pi M_{\mathrm{molc}}^3}\right)^{0.5}\left(\frac{\rho_g^2}{\rho_l}\right)\exp\left(-\frac{4\,\pi\, r_{\mathrm{crit}}^2\sigma}{3K_B T}\right) \quad (1)$$

where q_c is the condensation coefficient which is generally taken as unity, K_B is the Boltzmann constant, and η is a non-isothermal correction factor which is given by the following relation [46]:

$$\eta = 2\left(\frac{\gamma-1}{\gamma+1}\right)\left[\frac{h_{lg}}{R\,T}\left(\frac{h_{lg}}{R\,T}-\frac{1}{2}\right)\right] \quad (2)$$

where h_{lg} is the equilibrium latent heat, γ is the ratio of specific heat capacities and R is the gas constant. The critical radius of nucleation is determined by the Kelvin–Helmholtz formula in the following form [9]:

$$r_{\mathrm{crit}} = \frac{2\sigma}{\rho_l RT \ln(S)} \quad (3)$$

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