Applied Thermal Engineering 128 (2018) 320–334

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Accurate and efficient computations of phase-changing flows in thermal vapor compressors

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ARTICLE INFO

Article history:
Received 2 March 2017
Revised 15 June 2017
Accepted 25 August 2017
Available online 1 September 2017

2010 MSC:
00-01
99-00

ABSTRACT

This paper focuses on the limitations of single-phase computations which have been widely applied to the numerical simulations of flow fields around thermal vapor compressors (TVCs), and provides computational improvements through multi-phase flow modeling and analysis. In order to capture the multi-phase flow physics accurately and provide reliable results, several numerical methods and models, including the shock-stable multi-phase AUSMPW+ scheme, phase-changing models, cell-by-cell adaptive mesh refinement technique, and the IAPWS-97 equation of states, are combined into a numerical solver. We then simulate various TVC systems and compare the computed system performance and local flow physics between the single- and multi-phase computations. Based on the computational results and comparisons, we examine phase-changing process and its influence on two major local physical features, namely shock-train region and shear layer.

1. Introduction

Recently, desalination technology has become prominent as water shortages have become rampant in many countries around the world. It can be categorized into thermal approaches – such as multiple effect distillation and multi-stage flash – and membrane-based approaches – such as sea water reverse osmosis, brackish water reverse osmosis, electro dialysis or reversed electro dialysis. Reverse osmotic desalination technology has attracted particular attentions owing to its high efficiency. However, thermal desalination process still remains dominant in many geographical regions including Gulf Council countries due to the sea water condition known as 4H: High salinity, High turbidity, High temperature and High marine life [1].

Thermal vapor compressor (TVC) is a key system for improving the efficiency of thermal desalination plants. TVC system has two inlets: the primary nozzle to inject steam with high pressure and temperature (called the primary steam), and the suction nozzle to entrain steam with low pressure and temperature (called the suction steam). Fig. 1 shows the schematic of a TVC system.

Thermal desalination plant is generally composed of multiple desalination devices, which uses saturated steam to acquire fresh water. The pressure and temperature of the steam decreases as it passes through these multiple devices, consequently leading to the gradual diminution of desalination efficiency. The TVC system serves to entrain and repressurize the steam through the suction nozzle with the highly compressed primary steam. In this sense, the performance of the TVC is generally evaluated in terms of the entrainment ratio (ER), which is defined as the ratio of the mass-flow rate between the suction and primary nozzle. Predicting the entrainment ratio of the TVC accurately is vital in the preliminary design state of desalination plant, because it directly determines with the overall efficiency of desalination plant. For example, Fig. 2 explains the role of the TVC which determines the relationship between expected desalination capacity at each stage and the entrainment ratio of the TVC. Thus, improving the suction performance of the TVC is one of top priorities in desalination engineering fields. Complex flow physics inside the TVC, however, makes it difficult to provide reliable and accurate results for engineering analysis and design.

When the primary steam is released from the nozzle exit, a shear layer is developed due to the velocity difference between the supersonic core flow and the stationary surroundings. Meanwhile, continuous expansion in the diffusing part of the primary nozzle induces an over-expanded condition which generates shock wave at the primary nozzle exit. As a result of the interaction between successive shock/expansion waves and the free shear

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http://dx.doi.org/10.1016/j.applthermaleng.2017.08.149
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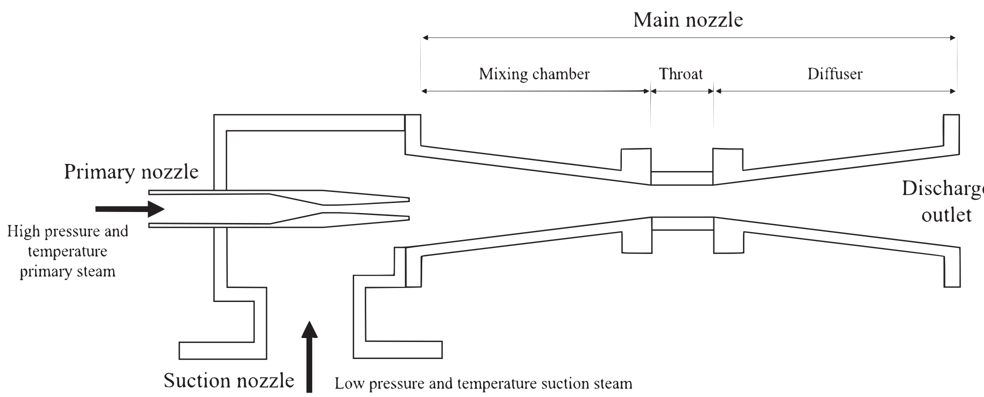

Fig. 1. Schematics of TVC system.

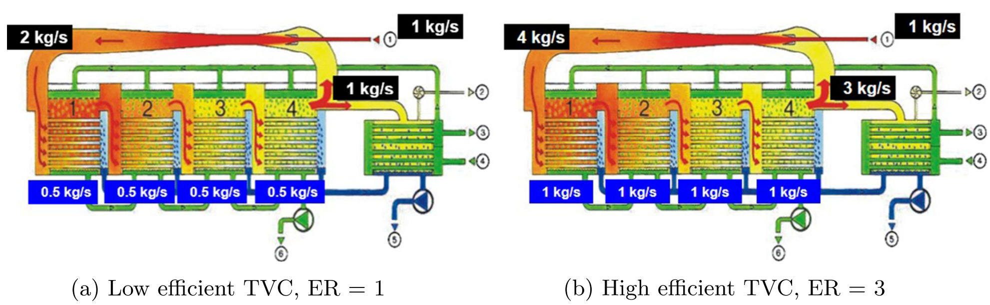

Fig. 2. Relation between entrainment ratio of TVC and expectable capacity in each desalination unit.

layer, the diamond-shaped shock-train is formed until the supersonic core flow is decelerated into a subsonic flow condition.

The entrainment effect of the TVC arises from the momentum transfer of the supersonic core flow through the shear layer. Unlike a single-phase flow fields, however, the phase-changing phenomenon – namely, the condensation and evaporation occurring through the repetitive expansion fans and shocks – complicates the entrainment process. Furthermore, the resolution of the shear layer is a critical factor for reliable and accurate computations because it determines the structure of the momentum transfer and the supersonic core flow.

Numerous studies have been conducted to understand the flow structures within the TVCs and to predict suction performance accurately. Sriveerkul et al. [2] validated their computations with experimental data by comparing the entrainment ratio, and explained the effects of geometrical variables on the flow structure. Wenjian cai et al. [3] investigated the influence of two geometric parameters (the primary nozzle exit position and mixing section convergence angle) upon the entraining performance. Sharifi et al. [4] compared the suction performances of five TVC models by changing the converging duct angle. However, all these studies assumed the working fluid as an ideal gas, and neglected the effects of the phase-changing phenomenon. Although these results can be assumed to be reasonable under low operating pressure, the pressure range for computational validity is rather ambiguous, and it is not physically clear why single-phase computations could yield acceptable entrainment ratio and flow structure. Recently, further researches indicated that the modeling on the phase-changing phenomenon is necessary for reliable and accurate computations. It was observed that the predicted entrainment ratio obtained by two-phase computation was greater than that of single-phase computation [5,6]. This manifested that further investigations are essential to evaluate the capability of two-phase numerical modeling and to unveil the detailed local flow physics affecting the entrainment ratio.

From this perspective, the present work focuses on accurate computations of flow fields around a TVC system with realistic operating conditions that have not been taken into account previously. As a baseline numerical flux, AUSMPW+_N scheme is used within the framework of finite volume method, which is known to be robust and accurate for single- and multi-phase shock capturing [7]. The IAPWS-97 formulation is adopted as an equation of state to reflect real fluid properties with reasonable computational efficiency. The grid dependence of the present computations is efficiently minimized through an adaptive mesh refinement technique. Phase-changing process is taken into account with two distinct models – the Hertz-Knudsen equation-based model and the nucleation model. The numerical framework integrating the above methods is evaluated with well-known validation cases such as the ejector problem and the condensing nozzle experiments of Moore, Moses and Stein. Then, we concentrate on the main objective of the present work, the numerical computations of phase-changing flows inside a TVC system with various operating conditions. The computed results are compared with those of single-phase computations and with the experimental data provided by Doosan Heavy Industries. Finally, local two-phase flow physics, which plays an important role in determining the suction performance of the TVC system, is examined based on the computed results.

2. Governing equations

The present computations are based on the homogeneous mixture model that uses mass-fraction to describe two-phase flow fields. In the homogeneous flow theory, the relative motion between each phase is not considered, and a mixture is treated by a set of pseudo-fluid elements whose properties are some averages of each phase component. This is based on the view point that each phase can be properly described by a continuum obtained