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International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2014

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Two-dimensional Numerical Analysis on Ejector of Vapour Jet Refrigeration System

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ABSTRACT

A vapor jet refrigeration system (VJRS) is an alternative to the conventional mechanically driven vapor-compression refrigeration system. The VJRS utilizes supersonic ejector as thermal compressor and has the potential to reduce energy consumption and utilize low grade energy for driving the refrigeration systems. In the present study, the performance characteristics of VJRS ejectors with R134a as refrigerant have been investigated numerically using commercial CFD software. For the numerical simulations on the selected ejector, generator temperature is varied from 55^oC to 80^oC, the condenser temperature is varied from 20^oC to 35^oC, and the evaporator temperature is varied from -10^oC to 10^oC. The numerical results obtained contribute to understanding the local structure of the flow. Moreover, the results help in identifying the optimum operating condition for each value of ejector area ratio.

1. INTRODUCTION

Ejector refrigeration system is thermally driven technology that has been used for cooling applications. An ejector is a device that can entrain a low-pressure stream by using a high-pressure motive stream. In general, it consists of a primary driving nozzle, constant area mixing section, and diffuser. The ejector system entrains the secondary stream through shear action generated by the primary jet and the pressure difference between the two fluids. A shear mixing layer is formed at the interface of the primary and the secondary fluids which entrains the secondary flow with low velocity. In shear mixing layer the secondary fluid is accelerated and the motive fluid gets decelerated (Lijo *et al*., 2010). In the shear mixing layer, there is a region that corresponds to sonic velocity which is called secondary choking region. The efficiency of this ejector system is relatively very low as compared to other fluid transport devices. However, its major advantages are that it has simple structure with no moving parts and it is cheaper while compressing and transporting a large amount of fluid with low grade energy. For these two reasons the ejector system has been used for refrigeration purposes, crude oil distillation, petrochemical processes, hybrid vacuum systems, metals vacuum degassing and space simulation.

Over the years much research has been carried out to design and evaluate ejector systems in refrigeration field. Main motivation of the research is to entrain maximum secondary flow for a given primary flow rate and operating conditions and compress the entrained fluid to required condition for condensation. In an ejector, the area ratio of constant area mixing chamber and nozzle throat area is known as 'ejector area ratio'. In the present study, the effect of area ratio of ejector at various operating conditions has been analysed. Literature review shows that Selvaraju and Mani (2006), Bartosiewicz *et al.* (2005) and Kim *et al*. (2006) have studied about the performance of ejector numerically as well as experimentally. Yen *et al*. (2013) have studied about the ejector performance with various area ratios by using different refrigerants as working fluid.

In the present work, two-dimensional analysis on the ejector geometry of VJRS (capacity = 3.5 kW) is carried out to examine the turbulent behavior and boundary layer distribution in the constant pressure mixing chamber. Also the performance of ejector at low generator temperature and low evaporator temperature has been evaluated. Turbulence effects in the ejector have been modeled using the realizable k-epsilon turbulence model (Bartosiewicz *et al.*, 2005). The present CFD results show that flow through cylindrical and rectangular ejectors have different characteristics. The results obtained from the present study may be more suitable for rectangular cross-section rather than cylindrical cross-section ejectors.

2. SYSTEM DESCRIPTION

Figure 1 shows the basic ejector system with dimensions. In the present work, ejector with three area ratios (4, 6 and 9) has been analyzed. The distance between the convergent-divergent nozzle exit and the inlet of the constant area mixing chamber is optimized for the given area ratio. Diffuser divergent angle is taken as 4°. It is assumed that the ejector has unit thickness and the secondary fluid is entrained from both the side. The throat diameter (D_t) and length of divergent portion of nozzle (L_n) correspond to the area ratio used in the present study.

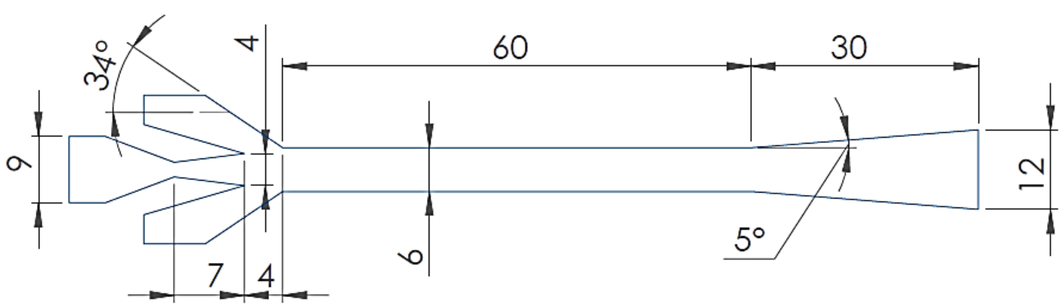

Figure 1: Ejector geometry (all dimensions are in mm)

3. COMPUTATIONAL METHODOLOGY

The flow in the ejector of VJRS is typically compressible and turbulent. The present study employs realizable *k*-*ε* turbulence model to describe the turbulent behavior in the ejector. The density-based implicit solver is used to solve nonlinear governing equations. In addition, focus has been on the 2-D steady flow analysis. Mesh consists of triangular elements everywhere except near the wall of the constant area mixing chamber and the convergent divergent nozzle where quadrilateral elements are used. The grid has been refined in the region where the primary and the secondary flows interact. Adaptive mesh size is selected with respect to the change in operating condition (Kim *et al.*, 2006). Moreover, systematic grid convergence studies have been performed to optimize the mesh size.

The validation studies have conducted with the experimental result of Selvaraju and Mani (2006). The validation studies show that CFD software is a reliable tool to analyze the flow physics in the ejector. The properties of refrigerant R134a have been calculated using NIST real gas models.

3.1 Governing equations

The flow in the ejector is described by compressible fluid flow conservation equation such as mass, momentum and energy. Generally Navier–Stokes equations are suitable for the analysis of variable density flows (Selvaraju and Mani, 2004). The governing equations are given below.

Continuity equation:

$$\frac{\partial P}{\partial T} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}[\rho u_i u_j + P\delta_{ij} - \tau_{ji}] = 0 \tag{2}$$

Energy equation:

$$\frac{\partial(\rho e_0)}{\partial t} + \frac{\partial}{\partial x_j}\left[\rho u_j e_o + u_j P + q_j - u_i \tau_{ij}\right] = 0 \tag{3}$$

4. RESULTS AND DISCUSSION

In the present study the flow characteristics in an ejector for three area ratios have been presented. For each area ratio the generator temperature (T_g) is varied from 55^{o}C to 80^{o}C and evaporator temperature from -10^{o}C to 10^{o}C at an interval of 5^{o}C as the interval. Figures 2 to 4 show the variation of entrainment ratio with generator temperature by keeping the evaporator temperature constant for three values of ejector area ratio. Figures 2 to 4 show that entrainment ratio decreases with increase in generator temperature.

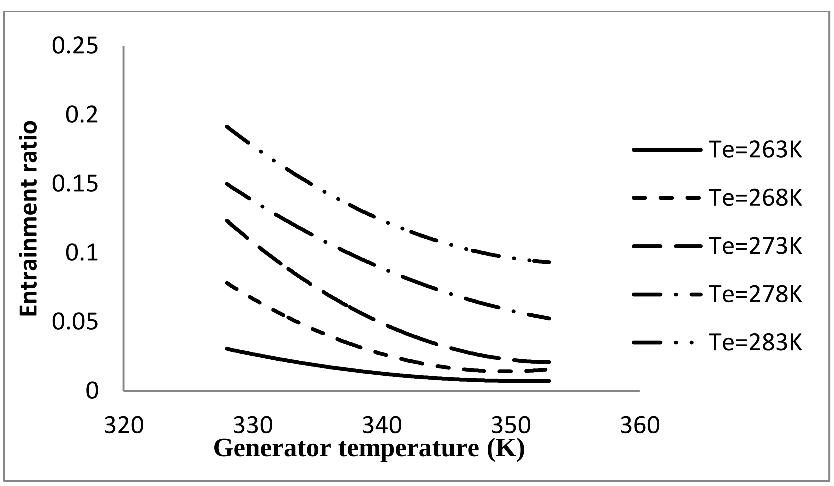

Figure 2: Effect of T_g on entrainment ratio for area ratio 4

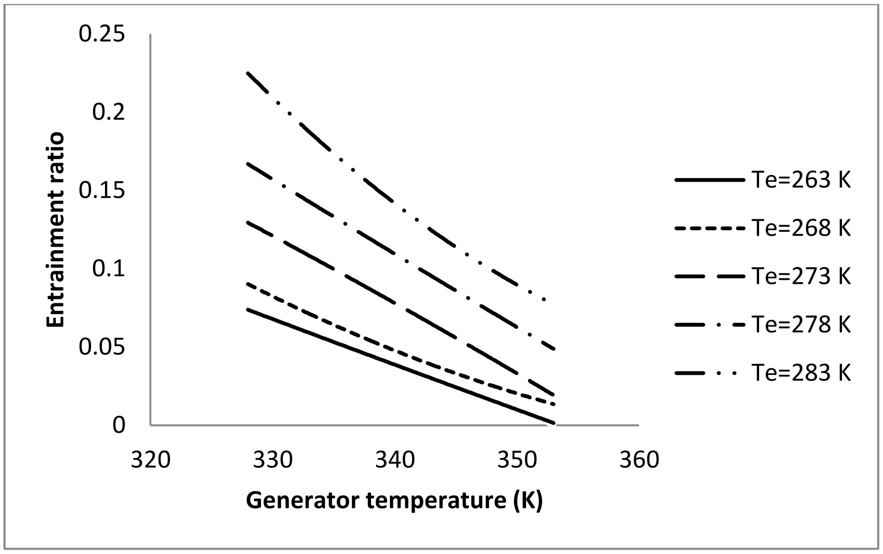

Figure 3: Effect of T_g on entrainment ratio for area ratio 6

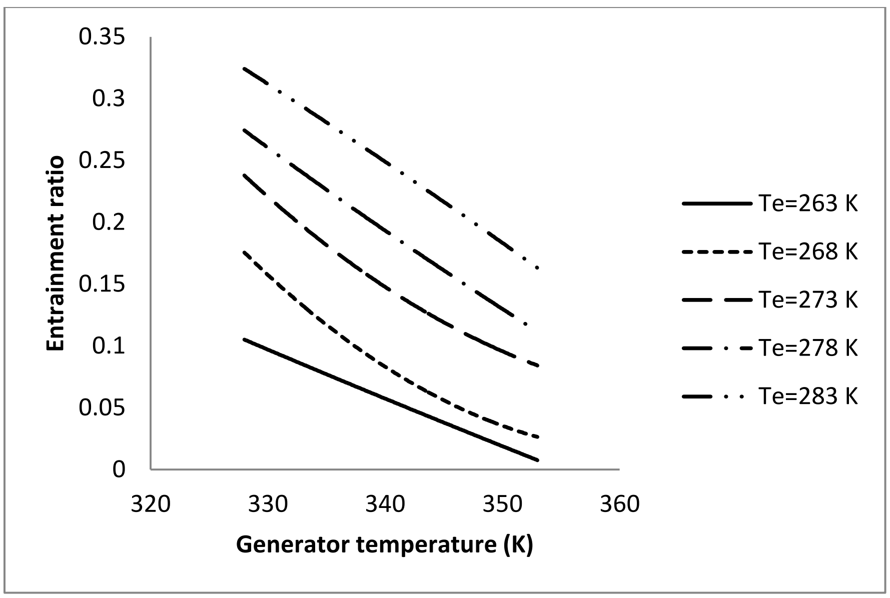

Figure 4: Effect of T_g on entrainment ratio for area ratio 9

Figures 5 to 7 depict the variation of entrainment ratio with evaporator temperature for different values of generator temperature. It is observed that entrainment ratio is increasing with evaporator temperature. At lower evaporator temperature the major entrainment is due to the shear action but at higher evaporator temperature major entrainment is due to the pressure difference between the nozzle exit and the evaporator. But the increase in the evaporator pressure leads to lower compression ratio of the ejector.

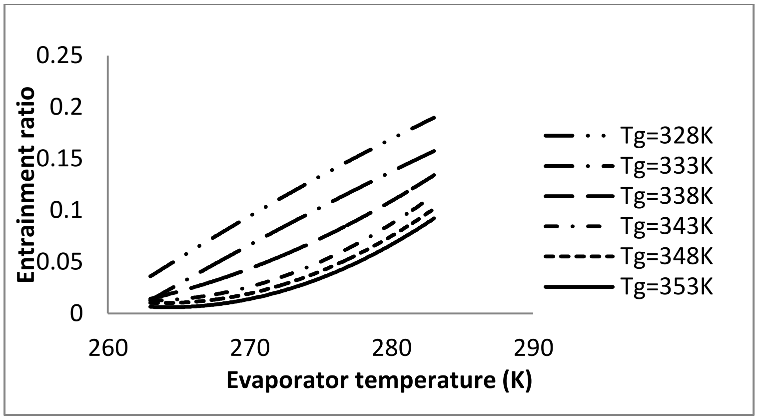

Figure 5: Effect of evaporator temperature on entrainment ratio for area ratio 4

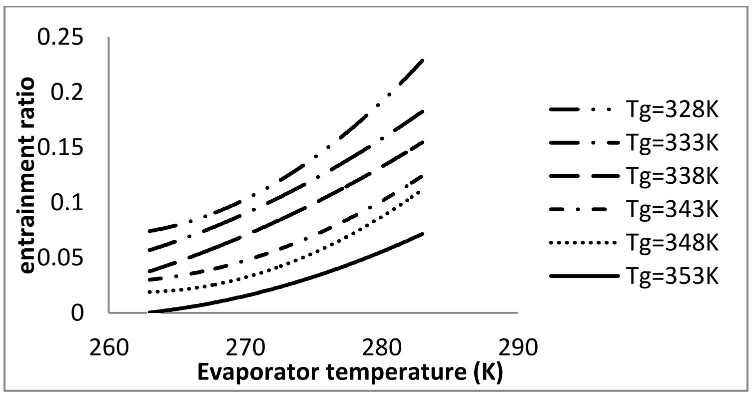

Figure 6: Effect of evaporator temperature on entrainment ratio for area ratio 6

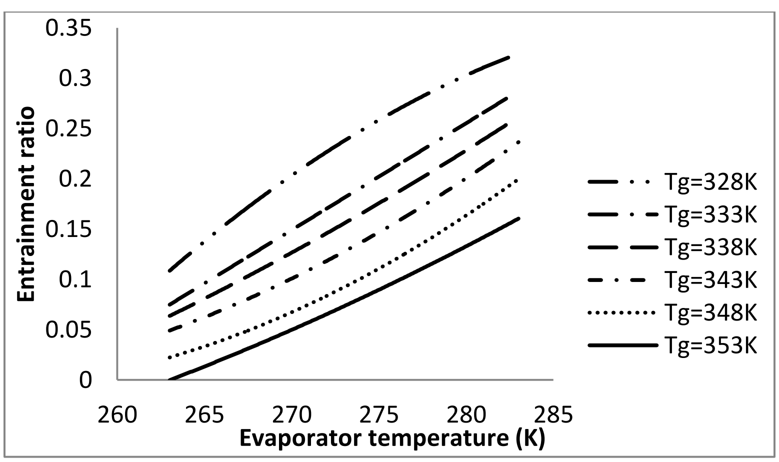

Figure 7: Effect of evaporator temperature on entrainment ratio for area ratio 9

For a given generator and evaporator pressure, entrainment ratio decrease with smaller change in magnitude with an increase in condenser temperature. But entrainment ratio reduces rapidly at a particular temperature, which is the critical condenser temperature at given generator temperature (Selvaraju and Mani, 2004). Figure 8 shows the critical temperature corresponding to the generator temperature. If the value of condenser temperature increases above the critical point reverse flow may occur and it leads to the reduction in entrainment ratio. It is observed that lower area ratio ejectors are able to achieve higher critical condenser temperatures.

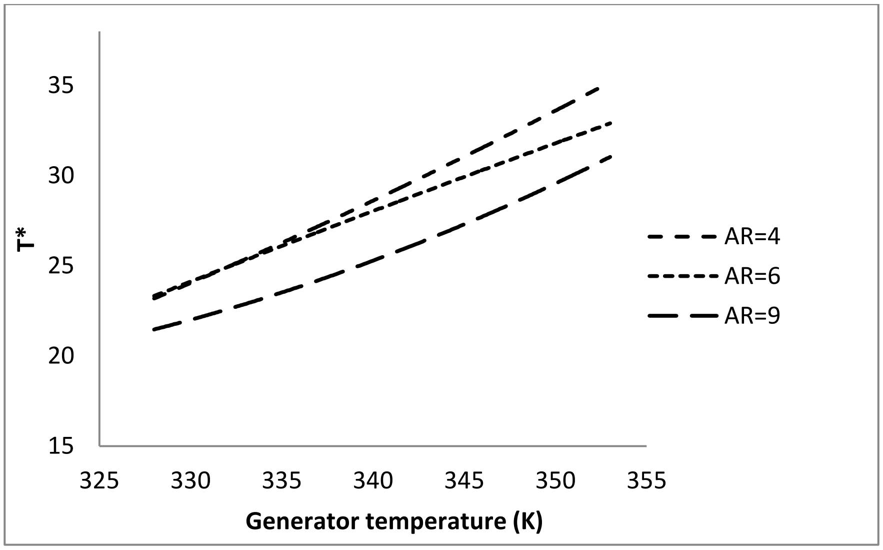

Figure 8: Effect of T_g on T*

Figure 9 depicts the effect of evaporator pressure on the high velocity jet from the convergent-divergent nozzle at constant T_g (328 K) and T_c (295 K). At lower evaporator pressure, nozzle exit is under-expanded that means expansion waves are formed at the exit of the nozzle. As the evaporator pressure increases, an oblique shock is observed at the exit of the nozzle. If the evaporator pressure is too high, it will cause a normal shock in the convergent-divergent nozzle leading to a subsonic flow at the inlet of the constant area mixing chamber. A subsonic flow in constant area tube will increase the flow velocity to a sonic velocity. If the flow at the diffuser inlet is sonic, the flow may accelerate and it will give a diverse effect to our requirement. The results show that evaporator pressure has the significant normal shock position in the constant area mixing chamber.

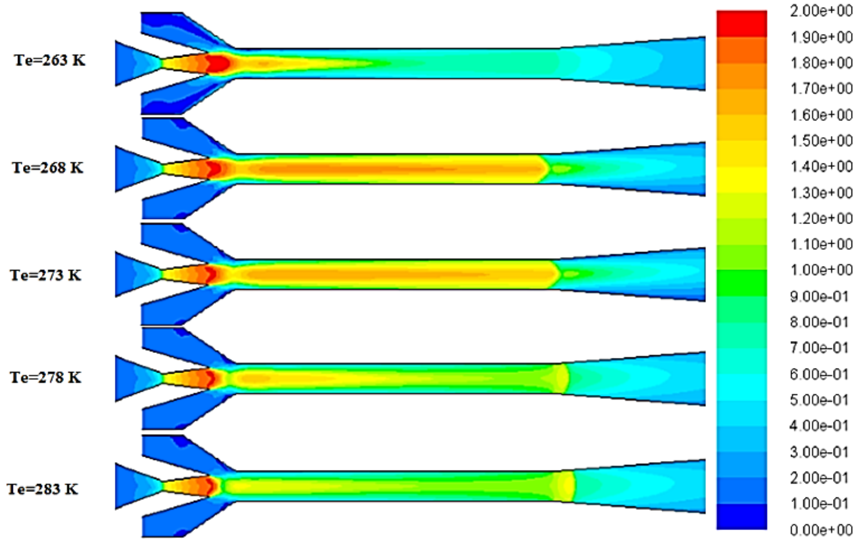

Figure 9: Effect of condenser temperature on supersonic jet

4. CONCLUSIONS

The influence of generator, evaporator and condenser temperatures on the system performance is studied numerically for three different area ratios. The present study suggests that the entrainment ratio decreases as the generator temperature increases for each area ratio. Higher entrainment ratio can be achieved by increasing the evaporator temperature. But higher evaporator pressure causes formation of oblique shock at the exit of the convergent-divergent nozzle. Lower evaporator pressure leads to expansion waves at the exit of convergent-divergent nozzle. So, evaporator temperature has significant role in designing and operation of a supersonic ejector. A higher value of area ratio corresponds to higher entrainment ratio for all the operating conditions. It is further observed that lower area ratios are able to achieve higher critical condenser temperatures.

NOMENCLATURE

T	Temperature
ER	Entrainment ratio
P	Pressure
ρ	Density
V	Velocity
AR	Area ratio
K	Turbulent kinetic energy
ϵ	Turbulent dissipation
Subscript	
c	condenser
e	evaporator
g	generator
Superscript	
*	Critical

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