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# Effect of Primary Vapour Quality on Entrainment of Secondary Vapour in Two-Phase Ejector Cooling System

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***Abstract*— The purpose of this paper is to study the level of entrainment in an ejector system for various working fluids at mixed phase conditions. Two-phase ejectors have attracted many researchers due to the capability to entrain more secondary vapour than single phase ejector. The predominant factor that differentiates two-phase ejector from single phase ejector is the co-existence of liquid and vapour phase during fluid flow. Efforts has been taken to ascertain the value of entrainment ratio at different operating condition for the given ejector system.A comparative study on entrainment of different two-phase working fluids has also been made. This study reveals that the entrainment ratio is very much influenced by thermo physical properties of the working fluids decides molecular weight, density and nature of the phase change phenomenon.**

***Keywords—Ejector cooling;two-phase ejector; entrainment ratio***

Nomenclature

| | | |
|---|---|---|
| $A$ | - | area in $m^2$ |
| $v$ | - | Specific volume in $m^3/kg$ |
| $h$ | - | Specific enthalpy in kJ/kg K |
| x | - | quality |
| m | - | mass in kg |
| V | - | velocity in m/s |
| $V_c$ | - | sound velocity in m/s |
| $\omega$ | - | entrainment ratio |
| $\rho$ | - | density in $kg/m^3$ |

Subscripts

| | | |
|---|---|---|
| $p$ | - | primary |
| $d$ | - | diffuser |
| $s$ | - | secondary |
| t | - | throat |
| m | - | mixing |
| e | - | exit |
| i | - | inlet |
| s | - | saturation |
| f | - | fluid |
| L | - | liquid phase |
| v | - | vapour phase |

## I. INTRODUCTION

A two-phase ejector cooling system involves the vital component, ejector in which liquid or two-phase vapour entrains saturated vapour from the evaporator. The prominence of the ejector relies on its credibility such as the low cost device, no moving parts and ability to handle two-phase fluids without damage and energy loss basically two-phase ejector cooling system is the heat-operated system which can utilise sources of low grade energy such solar energy or waste heat. In fact this is beneficial from environmental and economic point of view. In the cooling system the source heat is utilised for generating motive vapour that expands in the nozzle of the ejector. It is a general perception that the quality of motive vapour depends on the intensity of low grade energy.

Low temperature for air conditioning and refrigeration is achieved using refrigerants which are generally hydrocarbon derivatives. However there is growing pressure to adapt environmental friendly working fluids to mitigate the problem of ozone depletion. Thus fully halogenated chlorofluorocarbons (CFC) that contain only chlorine, fluorine and carbons have been phased out due to their emission into the atmosphere causes depletion of stratospheric ozone global warming. As an immediate solution and ideal substitutes for CFCs, hydro fluorocarbons (HFCs) and other organic and inorganic substances started ruling refrigeration industry at present. Accordingly three working fluids, namely R134a (tetrafluoroethane), R152a (difluoroethane) and RE170 (dimethyl ether) have been selected for this study.

## II. STUDY ON TWO-PHASE EJECTOR

Single–phase ejector has been studied by many authors [1,2]. The design theory of single-phase ejector has been establishedon the basis of perfect gas assumption with real gas properties [3,4]. Flow through nozzle has a well-established modelling. However, flow in the mixing chamber is difficult to understand. This complex mixing phenomenon in the mixing chamber can be analysed in the two-phase ejector cooling system based on the flow mechanism of single-phase ejector theory for achieving better flow condition and performance of the system and in turn to achieve high entrainment of secondary flow of the cooling system [5]. One dimensional model evolved in conjunction with gas dynamics can be used for analysis of two-phase ejector which requires different formulation due to the existence of liquid and vapour phase at different section of the ejector. The governing equation of mass, momentum and energy can be formulated by using thermodynamic principles along with quality of primary and secondary fluids.Figure 1 describes the schematic diagram of a two-phase ejector cooling system, while Figure 2 illustrates the two-phase ejector.

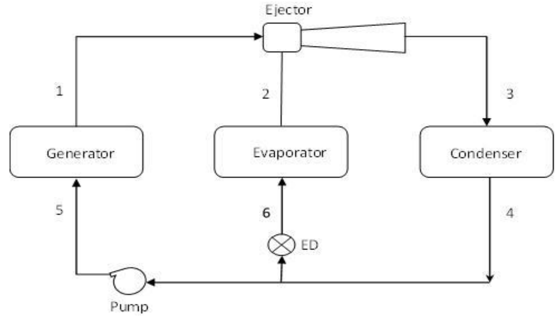

Figure 1 Schematic diagram of ejector cooling system

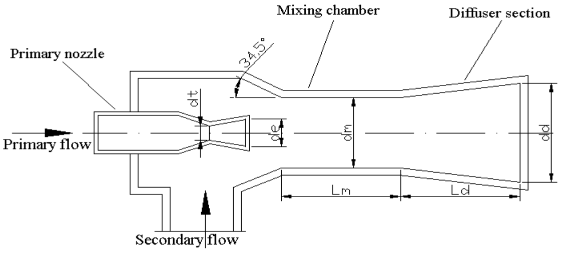

Figure 2 Schematic diagram two-phase flow ejector

A mathematical model is employed at different sections of ejector, such as, primary nozzle, suction chamber, mixing chamber and diffuser. Thus specific volume ($v_{pi}$) and specific enthalpy ($h_{pi}$) at the inlet section of primary nozzle can be expressed as,

$$v_{pi} = (1 - x_{pi}) v_{f,pi} + x_{pi} v_{s,pi} \quad (1)$$

$$h_{pi} = (1 - x_{pi}) h_{f,pi} + x_{pi} h_{s,pi} \quad (2)$$

The specific volume ($v_{pt}$) and specific enthalpy ($h_{pt}$) at the throat section of primary nozzle can be expressed as

$$v_{pt} = (1 - x_{pt}) v_{f,pt} + x_{pt} v_{s,pt} \quad (3)$$

$$h_{pt} = (1 - x_{pt}) h_{f,pt} + x_{pt} h_{s,pt} \quad (4)$$

The specific volume ($v_{pe}$) and specific enthalpy ($h_{pe}$)at the exit section of primary nozzle can be expressed as

$$v_{pe} = (1 - x_{pe}) v_{f,pe} + x_{pe} v_{s,pe} \quad (5)$$

$$h_{pe} = (1 - x_{pe}) h_{f,pe} + x_{pe} h_{s,pe} \quad (6)$$

The continuity, momentum and energy at the mixing chamber can be expressed as

$$m_p + m_s = m_m \quad (7)$$

$$m_p V_{pi} + m_s V_{si} = m_m V_m \quad (8)$$

$$m_p h_{pi} + m_s h_{si} = m_m h_m \quad (9)$$

The continuity, momentum and energy at the diffuser can be expressed as

$$\rho_{me} A_{me} V_{me} = \rho_{de} A_{de} V_{de} \quad (10)$$

$$m_{me} V_{me} = m_{de} V_{de} \quad (11)$$

$$m_{me} h_{me} + m_{me} \frac{V_{me}^2}{2} = m_{de} h_{de} + m_{de} \frac{V_{de}^2}{2} \quad (12)$$

The entrainment ratio is expressed as

$$\omega = \frac{m_s}{m_p} \quad (13)$$

The reduction in thermodynamic losses during expansion of primary fluid helps in creation of higher vacuum at the motive nozzle exit. This leads to improvement in entrainment.

## III. WORKING FLUIDS

Organic refrigerants always prove to be better working fluids as they could be used to achieve temperature below 0 °C in low temperature field [6]. However the Montreal protocol on stratospheric ozone depletion and the Kyoto protocol on global warming have made world community to choose right working fluids in cooling system. Investigations on performance of ejector cooling system using environmental-benign working fluids have been taken up by different research groups worldwide [7,8]. Every investigator or group of investigators have presented outcome of their theoretical and experimental studies precisely and in some instances more elaborately [9,10]. While collecting information on current status of research, it is observed that literature on ejector cooling system with single phase working fluids is plenty. Hence an attempt has been made to study the performance of two-phase ejector cooling system, which is common for the cooling systems operating at low temperature range of renewable energy sources. In ejector cooling system high pressure vapour produced in the boiler passes through a motive nozzle which produces vacuum in the suction chamber to entrain refrigerant vapour from the evaporator. In two-phase ejector system, one of the stream, that is, motive stream, is assumed to be a pure liquid or a wet vapour while the other stream enters as a dry and saturated vapour. It is noted that the working fluid in two-phase ejector cooling system plays an important role in the cycle analysis.

### *A. Desired properties*

A working fluid must not only have the necessary thermo-physical properties that match the application but also possess adequate chemical stability in the required temperature range. In general the selection criteria of working fluids rest on its sound thermo-physical properties which dictates necessary requirements such as, non-toxic, non-inflammable, low condensing pressure, low specific volume, low liquid specific heat capacity, high vapour specific heat capacity, high thermal conductivity of both liquid and vapour, low viscosity of both vapour and liquid. In addition, types of working fluid, fluid density, specific heat, latent heat, critical point, and thermal conductivity, specific volume at saturation conditions as well as saturation volumes are also the required thermodynamic properties considered for the selection of working fluid. Theseabove properties are discussed for the screening of potential working refrigerant fluid.

It is noted that the heat capacity of vapour has a small effect on the performance of the refrigerator than the critical temperature but is still significant. High volumetric capacities are associated with low value of specific heat. For maximum COP, an optimum value of specific heat exists. Heat capacity affect the performance of vapour compression cycleprimarily through its influence on the shape of the two-phase region or vapour dome on temperature entropy diagram. The optimum value of specific heat results in vapour dome that gives a small superheat this is the behaviour observed with most common refrigerants.

## IV. SIMULATION METHODOLOGY

The performance analysis of two-phase ejector cooling system has been simulated by using a computer code written in FORTRAN77. It is assumed that the cooling system is powered using a low grade thermal energy and hence the operating source temperature is assumed to vary from 60°C to 90°C.

The working fluids experience primary flow choking at the nozzle throat and secondary flow choking at the hypothetical section before mixing.Conditions for choking are identified at appropriate section where the sonic velocity equals flow velocity. Since the working fluid in nozzle, mixing chamber and diffuser exists in two-phase, the sonic velocity is computed using the relationship available in literature[11] as,

$$V_c = \sqrt{\left(\frac{\partial p}{\partial \rho}\right)_s} = \left(\frac{v_m^2\left(h_{V,s} - h_{L,s}\right)}{\left(v_{V,s} - v_{V,s}\right)\left(\partial h_m - v_m\right) - \partial v_m\left(h_{V,s} - h_{L,s}\right)}\right)^{\frac{1}{2}} \tag{14}$$

Thermo-physical properties are determined using data available in literature [12]. This code is capable of performance parameters such as critical entrainment ratio, critical COP and area ratio.

## V. RESULTS AND DISCUSSION

The simulation code has been so developed that it can account for the variation of quality of refrigerant pure liquid phase to (x=0) to dry and saturated vapour (x=1). Figure 3 to Figure 8 describe the variation of critical entrainment ratio with respect to boiler temperature. The increase in boiler temperature leads to increases in the boiler pressure.

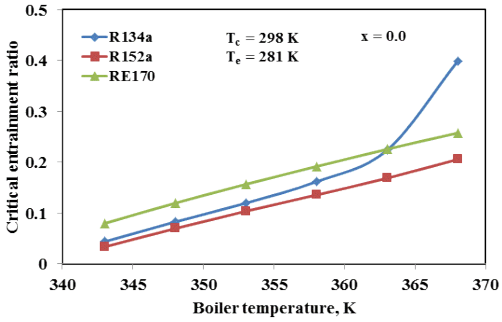

Figure 3 Effect of Boiler temperature on critical entrainment ratio

The higher pressure stream entering the ejector comes out of the motive nozzle at higher kinetic energy.This helps to increase the momentum of the secondary vapour from the evaporator and hence leads to improved entrainment.

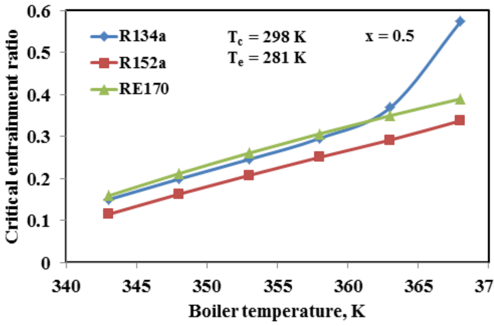

Figure 4 Effect of Boiler temperature on critical entrainment ratio

Thus when boiler temperature increases critical entrainment ratio also increases. This is true for all selected working fluids at different quality of motive fluid. Figure 3 to Figure 5 show the effect of boiler temperature on critical entrainment ratio for motive vapour quality of 0, 0.5 and 1. It is noted from Fig. 3 thatRE 170 performs better than other two working fluids for the range of boiler temperature ending at 363 K. However R134a performs better at higher boiler temperature.

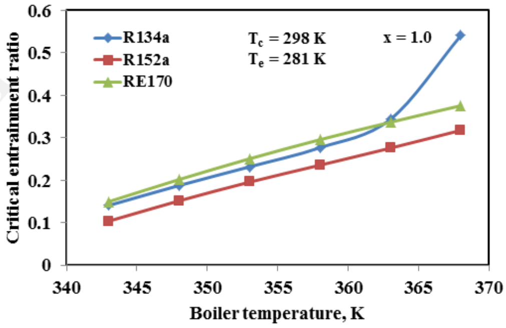

Figure 5 Effect of Boiler temperature on critical entrainment ratio

It can be seen that the quality of motive vapour very much influences the critical entrainment ratio. It is observed that the increase in quality of motive fluid from 0 to 0.5 indicates an increase in critical entrainment ratio.

The perception of increase in critical entrainment ratio when quality of motive vapour increased becomes deceptive while looking at Figure 6 to Figure 8.

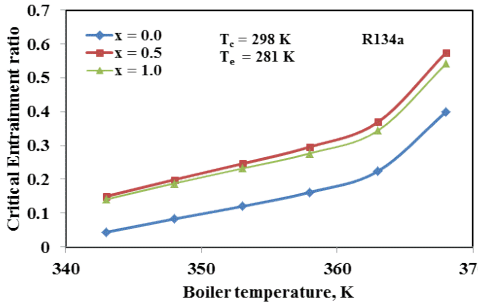

Figure 6 Effect of Boiler temperature on critical entrainment ratio for R134a

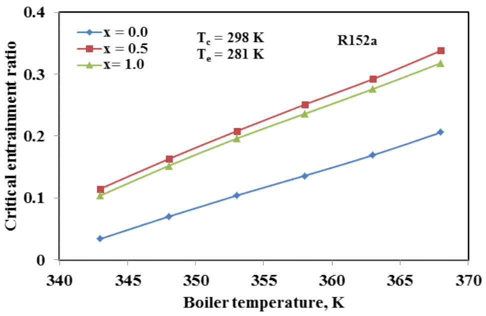

Figure 7 Effect of Boiler temperature on critical entrainment ratio for R152a

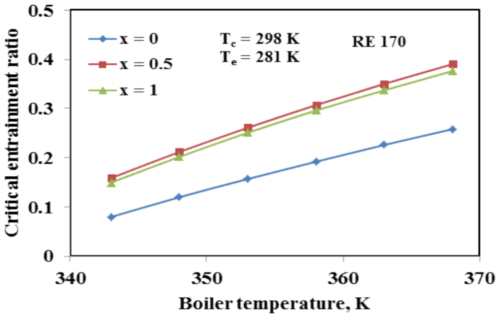

Figure8 Effect of Boiler temperature on critical entrainment ratio for RE 170

It is observed from Figure 6 to Figure 8 that the critical entrainment ratio decreases to a lower value when the value of quality of motive fluid or vapour equals to 1. This phenomenon is common for all selected working fluids.

## VI. CONCLUSIONS

The patterns of variation of critical entrainment with boiler temperature are almost identical for all working fluids except R134a. Critical entrainment increases with increase in boiler temperature. However the critical entrainment increases first and then decreases to a lower value when the quality of motive vapour increases from 0 to 1. Among the selected working fluid RE170 gives better performance for a wider range of boiler temperature. However R134a yields better performance at higher boiler temperature in comparison with other working fluids at respective quality of motive vapour.

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