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ABSTRACT

Performance of vapour jet refrigeration system is based on satisfactory operation of ejector. Hence, the present work focuses on enhancing the performance of the ejector using three-dimensional CFD analysis with refrigerant R134a by introducing swirl in the primary stream of ejector, using swirl generators. In literature, compressible and two-dimensional axisymmetric swirl flow ejector with ideal gas assumption has been investigated. The novelty of the present work is the three-dimensional analysis of swirl flow ejector working with refrigerant R134a, considering real gas behavior using k-ε turbulence model. Real gas thermodynamic behaviour and transport properties of R134a have been obtained using 'NIST Real Gas Model' that uses REFPROP subroutines. Shock patterns, Mach number, radial velocity and tangential velocity variations along the ejector have been studied for a set of operating conditions. Results indicate that the entrainment ratio gets improved for the ejector in presence of swirl by about 6% as compared to the ejector with no swirl, thereby improved coefficient of performance of vapour jet refrigeration system.

1. INTRODUCTION

Vapour Jet Refrigeration (VJR) system is preferred among various heat operated refrigeration systems, because it has potential of utilizing low temperature heat source, consumes less than 1% of high grade energy causing lesser atmospheric pollution. Ejector, a thermal compressor, is one of the crucial components of VJR system. Performance of the whole system is based on the satisfactory operation of the ejector. Hence, it has to be designed carefully and effectively to realize good performance of the whole system. Key criteria for enhancing the performance of the ejector demand higher entrainment and better mixing of the primary and secondary streams, resulting in better momentum exchange. Swirl flow induces turbulence, which aids in better mixing of fluids and swirl flow intensity decays downstream of the flow within a few pipe diameters. Swirl flows could be generated by the application of a spiral motion to the axial flow by use of various swirl generating methods. A swirl velocity component, also known as the 'azimuthal', 'transverse' or 'tangential' velocity component, is thereby imparted to the flow, resulting in a helical winding of the streamlines (Fokeer, 2006). Some of the methods used are tangential inflow, propeller type swirl generators, guided vanes, swirler, honeycomb structures, twisted tape inserts, wires or tubes mounted at the inlet, rotating pipes, etc. (Gupta, *et al*., 1984). The present work focuses on enhancing the performance of the ejector using three-dimensional CFD analysis with R134a by introducing swirl in the primary stream of ejector using swirl generators.

2. LITERATURE

VJR system has been studied for a long time, focusing on enhancing the performance of the ejector. Entrainment ratio is one of the key performance parameters, defined as the mass flow rate of secondary stream entrained for a given mass flow rate of primary stream. It depends on the ejector geometry and operating conditions. Plenty of research work has been carried for analysing the influence of ejector geometry and operating conditions on the ejector performance. Several techniques have been adopted by research groups, viz., one-dimensional analysis, CFD based numerical analysis, experimental studies and flow visualisation studies. CFD (Computational Fluid Dynamics) is an effective diagnosing numerical tool which aids in understanding the real flow physics inside the ejector, such as shock pattern, turbulence effect, circulation of flow, etc., and also in achieving optimum ejector geometry for maximum efficiency without causing harm to the environment compared to experimental studies.

Ejector working with steam used for refrigeration applications has been analyzed for its performance study with the aid of CFD techniques with 3D axisymmetric geometry, using realizable k-ε turbulence model (Sriveerakul *et al*., 2007). Bouhanguel *et al.* (2009) carried out three-dimensional analysis of supersonic air ejector operating with and without secondary flow. Performance analysis of supersonic ejector using CFD and experimental analysis under different modes, ranging from on-design to off-design conditions has been carried out (Bartosiewicz *et al*., 2005). Different turbulence models, namely, k-ε, RNG k-ε, RSM and two k-ω have been tested and compared with experimental results from literature. The effect of suction tube which entrains secondary flow on entraining performance is studied by comparing the axisymmetric and three-dimensional analysis (Pianthong *et al.,* 2007). Rusly *et al*. (2005) have studied the flow behavior of the ejector with CFD analysis. Selvaraju and Mani (2006) carried out performance analysis with R134a using three-dimensional CFD analysis and experimentally validated the same for refrigeration capacity of 0.5 kW (Selvaraju and Mani, 2005). Among the new techniques/ methodologies for enhancing the ejector performance, swirl ejector that is introducing swirl effect to the primary stream is one of the developing/ growing techniques. The effect of swirl ratio on entrainment ratio has been analysed by keeping all other geometric parameters fixed and an optimum value of swirl ratio is obtained that maximizes the entrainment ratio (Park, 2009a). Two-dimensional studies on ejector have been analyzed with swirl effect of primary stream, considering the flow as compressible, steady and turbulent in nature with ideal gas assumption (Park, 2010). The computational domain is axisymmetric with induced primary swirl flow solved for various swirl to axial component ratios. The author evaluates the effect of swirl motive stream inflow on entrainment ratio by presenting Mach number, isobars, radial velocities and shock patterns. He observed that swirl effect increases the contact time between the motive and suction streams and the effect of shear force, thereby entrainment ratio could be increased. The stability of ejector has also been analysed for ejector to operate in double choking mode (Park, 2009b).

3. WORKING PRINCIPLE OF EJECTOR

A typical ejector consists of four parts: primary nozzle, suction chamber, constant area mixing tube (also called ejector throat) and diffuser as shown in Fig.1. Primary stream or motive stream from the generator enters the ejector primary nozzle (a convergent-divergent nozzle) at high pressure and high temperature. Primary stream expands in the nozzle and exits at supersonic velocity.

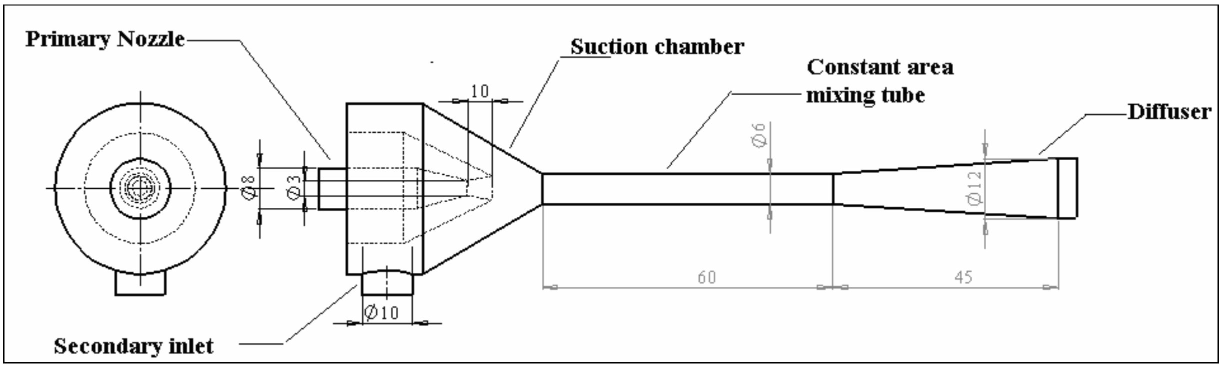


Figure 1: Schematic diagram of ejector

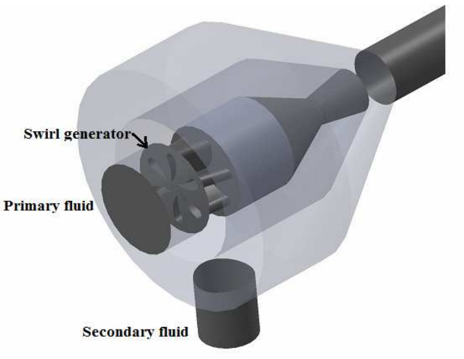
The momentum exchange between two streams entrains secondary stream from the evaporator due to pressure difference between two streams. Both streams mix together at constant pressure, exchange momentum, compressed partially through shock waves in the constant area tube and finally compressed further in the diffuser. A normal shock may occur anywhere in the mixing chamber according to the operating pressure conditions. The ejector has to be designed with utmost care in order to provide compression work thereby improved performance of the whole system. This is because its operation relies on the principle of interaction between two fluid streams at different energy levels.

4. CFD ANALYSIS

4.1 Ejector geometry

Ejector has been modeled, analyzed for 3.5 kW refrigeration capacity VJR systems focusing to operate at lower generator temperatures. The ejector without swirl as shown in Figure 1 has been analyzed for the on-design operating conditions. Also the same ejector geometry with swirl generator has been analysed and compared with the ejector without swirl for results in the form of the static pressure, velocity, Mach number and shock-pattern variations. The swirl ejector is designed with fixed swirl generator with a camber angle of 15° placed at a distance of 5mm from the primary nozzle entry, along with vane specification as shown in Figures 2(a) and (b) respectively.

(a)



(b)

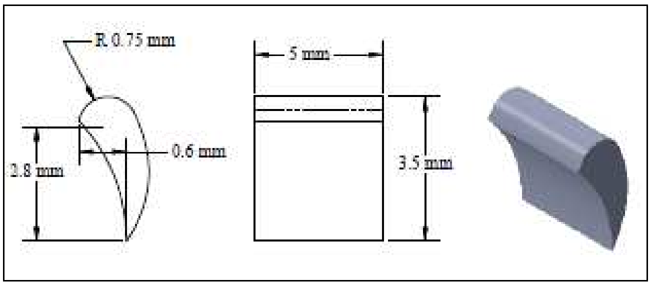


Figure 2: (a) Pictorial representation of swirl generator incorporated in the primary nozzle (b) vane specification

4.2 Governing equations

Flow in the ejector has been modeled with mass, momentum and energy equations along with turbulence equations (Selvaraju and Mani, 2005). Single phase flow is considered and the internal flow behaviour of the ejector has been analyzed. Steady, compressible and turbulent flow analysis has been carried out. The required degree of accuracy is obtained using unstructured mesh size of 1,50,000 cells with grid-adaption in critical areas of ejector like mixing chamber and mixing tube. The thermodynamic and transport properties of refrigerant R134a considering real gas behaviour, has been solved by using REFPROP subroutines (Lemon *et al.*, 2013).

4.3 Boundary conditions

Boundary conditions at inlet and outlet are given as total pressure, representing stagnation conditions at the primary, secondary stream entry and the exit of the ejector. The ejector has been operated at on-design condition of generator pressure of 16.75 bar absolute, evaporator pressure of 3.48 bar absolute and condenser pressure of 5.69 bar absolute. Also the ejector has been analysed for off-design conditions. Adiabatic and no-slip wall conditions are considered in the present analysis.

4.4 Solver and turbulence model

The ejector flow is generally three-dimensional, compressible and turbulent in nature. Two-dimensional analysis is available in literature with the assumption of very low suction velocity of the secondary stream. The study of ejector with motive swirl demands three-dimensional analysis which would give clear understanding of the flow physics inside the ejector. Density based solver with k-ε turbulence model and standard wall function has been used in the analysis. The convective terms in the governing equations are discretized using second order upwind scheme.

5. VALIDATION

Ejector without swirl has been validated with experimental results of Selvaraju and Mani (2006). The Entrainment Ratio (ER) has been obtained for the set of generator temperatures from 65°C to 80°C, condenser temperature of 27°C and evaporator temperature of 10°C. The deviation in entrainment ratio is found to lie within the ±10%.

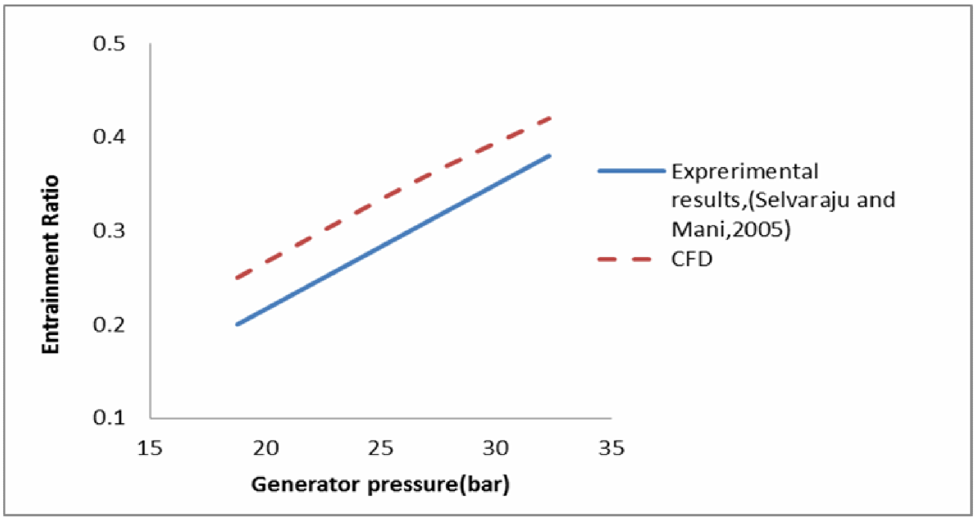


Figure 3: Effect of generator pressure on entrainment ratio

6. RESULTS AND DISCUSSION

The swirl generator is placed in the primary nozzle to induce swirl effect to the primary stream. The swirling effect induces turbulence, thereby enhances mixing of the two streams, which leads to better performance of the ejector. Pressure contours representing pressure variations (in Pa) along the ejector for no-swirl and swirl cases have been shown in Figures 4(a) and (b).

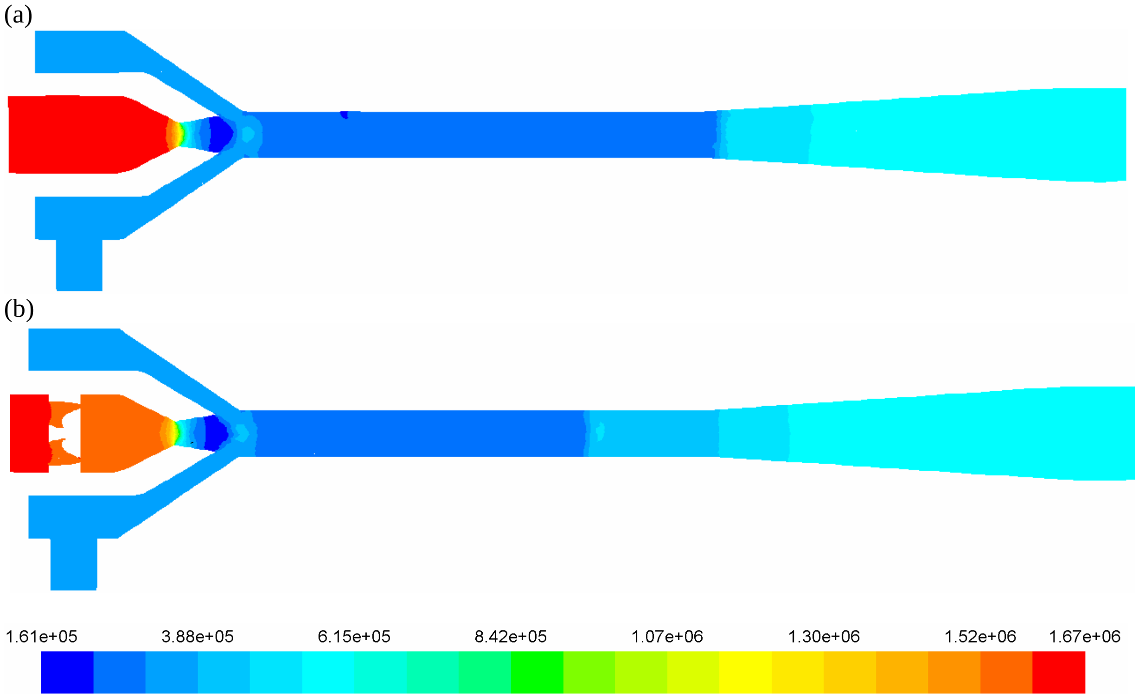


Figure 4: Pressure contours for (a) without swirl and (b) with swirl ejector

It has been observed that shock occurs at a relatively shorter distance from the entry section of constant area mixing tube, when compared to ejector with no-swirl. It indicates that swirl effect improves mixing of the two streams, thereby better momentum exchange occurs and pressure recovery has been obtained for a relatively shorter length of mixing tube.

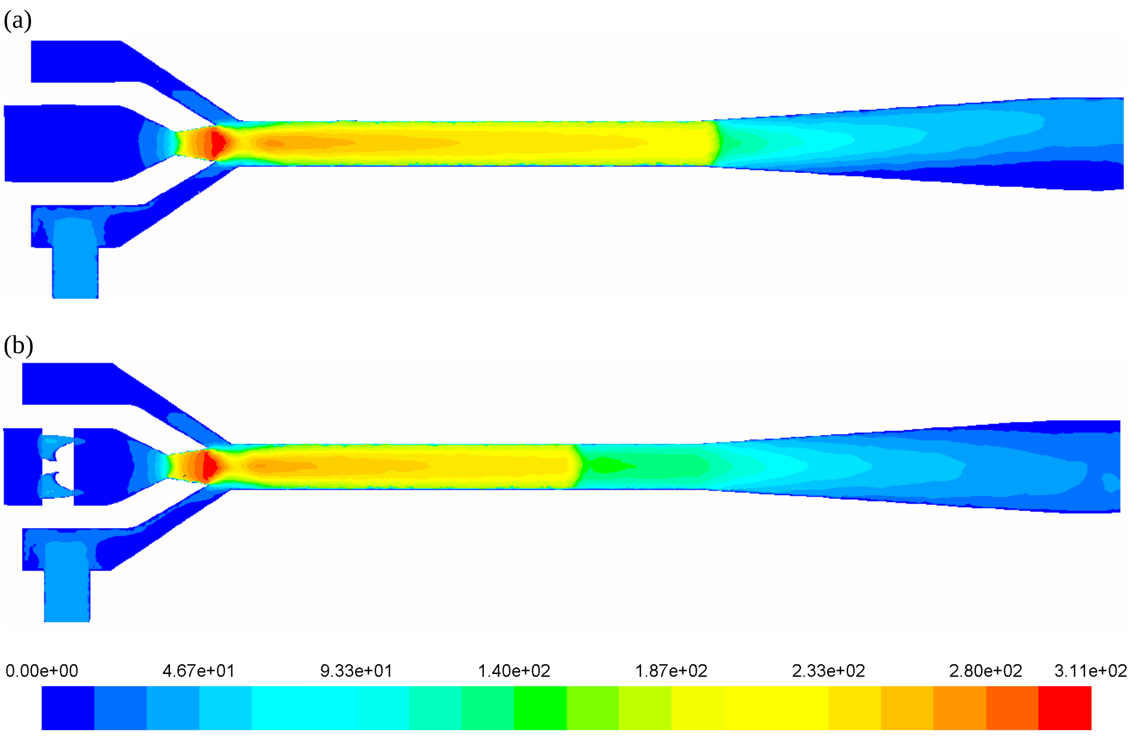


Figure 5: Velocity contours of (a) without swirl and (b) swirl ejector

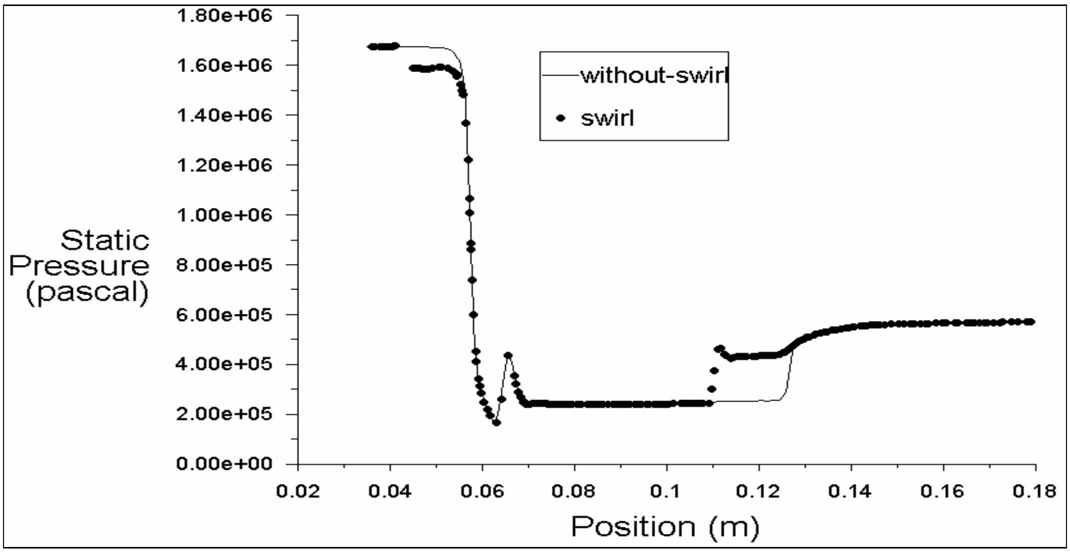


Figure 6: Static pressure plots of swirl and without swirl ejector along the axis

The ejector with swirl could operate for a wider range of operating conditions effectively, without shock occurring in the diffuser due to rise in primary stream pressure. The same could also be observed from the velocity contours representing variation of velocity (in m/s) along the central plane of ejector as shown in Figure 5. Static pressure distribution or variation along the axis of the ejector is plotted as shown in Figure 6. The pressure drop has been observed across the swirl generator in the primary nozzle entry, whereas constant pressure has been observed in the ejector without swirl.

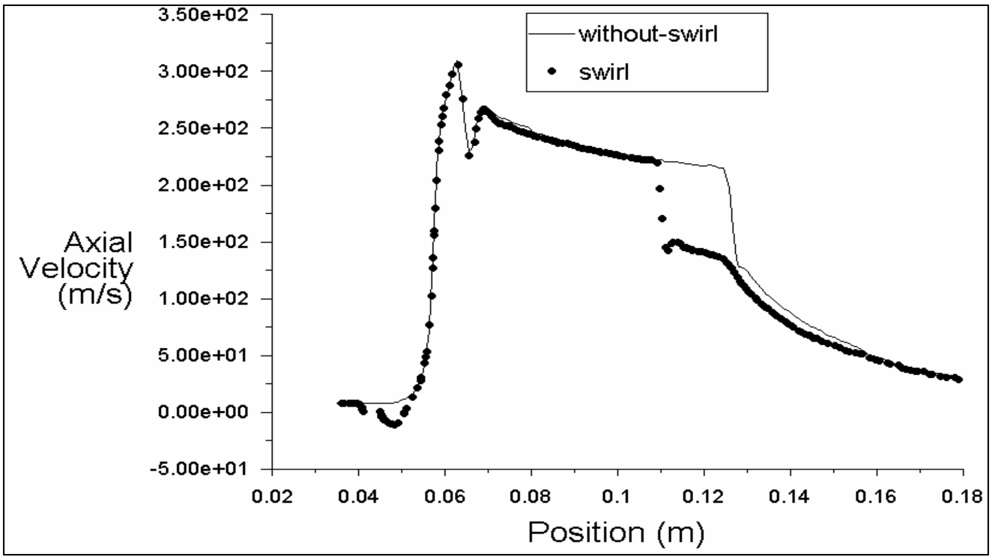


Figure 7: Axial velocity variation along the axis of ejector for swirl and without swirl ejector

Primary stream expands to supersonic velocity in the convergent-divergent primary nozzle and entrains the secondary stream. The secondary stream is accelerated to sonic condition due to momentum exchange between primary and secondary streams. Mixing of two streams occurs at constant pressure in the constant area mixing tube followed by a sudden pressure rise due to shock. In the diffuser, further pressure rise takes place. Axial velocity variation along the axis of the ejector as shown in Figure 7 denotes sudden drop in velocity due to shock and further reduction of velocity at the diffuser section could be observed.

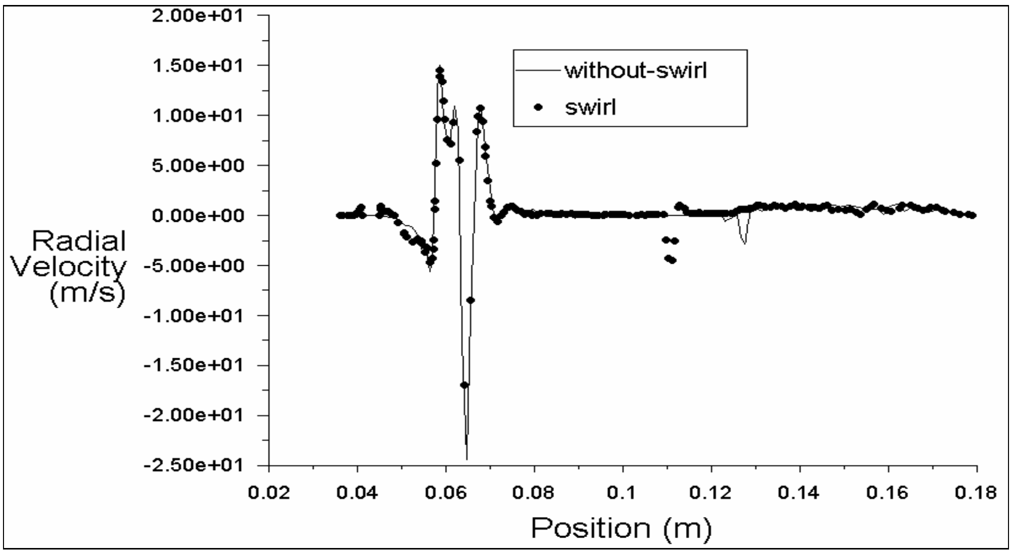


Figure 8: Radial velocity variation along the axis for swirl and without swirl ejector

Radial velocity has less influence of swirl effect of primary stream as observed from Figure 8. Tangential velocity gets substantially increased due to swirl effect for swirl ejector compared to no-swirl ejector as shown in Figure 9. Mach number variation along the axis of ejector in Figure 10 shows the reduction in Mach number due to swirl effect in case of swirl ejector as compared to ejector without swirl. A portion of Mach number plot is shown to represent the decrease in Mach number in case of swirl ejector as compared to ejector without swirl.

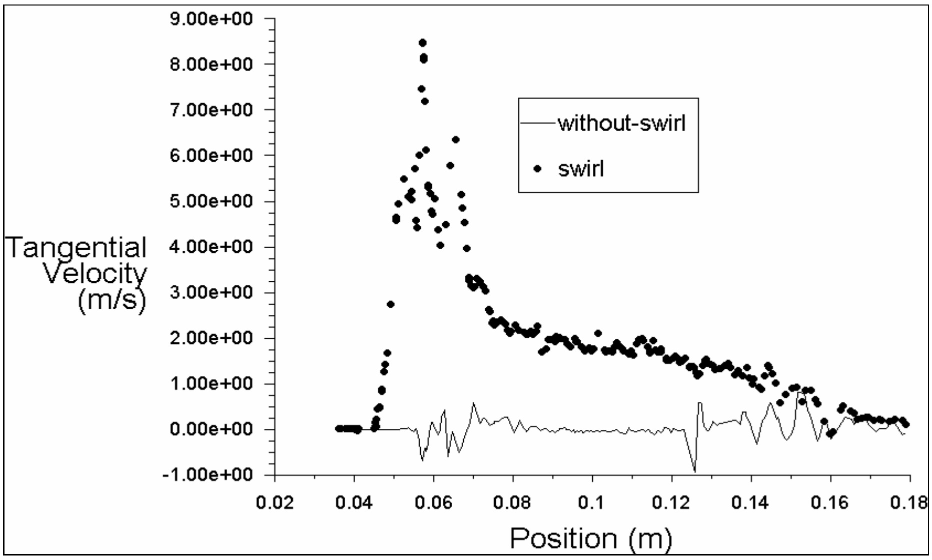


Figure 9: Tangential velocity variation along the axis for swirl and without swirl ejectors

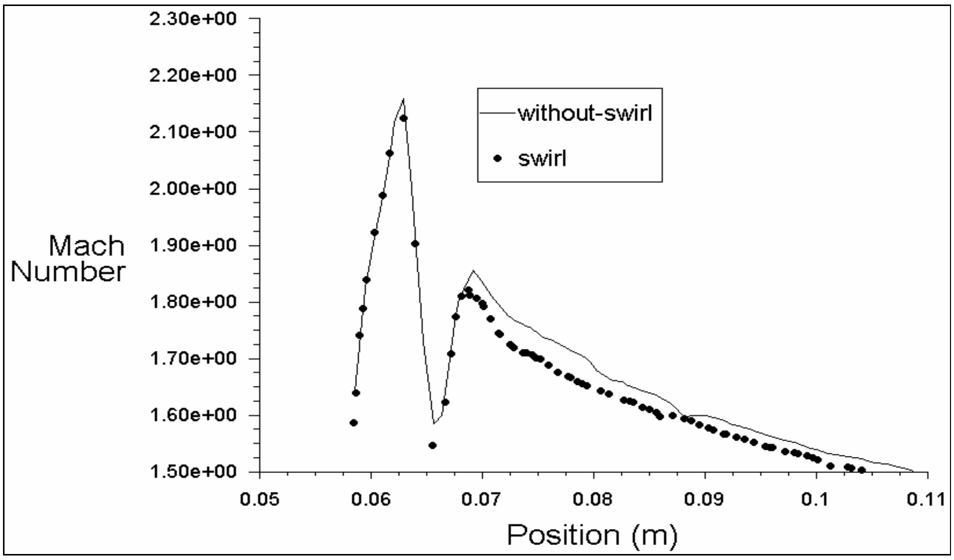


Figure 10: Mach number variation along the axis for swirl and without swirl ejector

Turbulent kinetic energy (TKE) variation along the axis of the ejector for swirl and no-swirl cases has been shown in Figure 11. An increase in turbulent kinetic energy at the primary nozzle exit (observed in Figure 11, as a first peak) due to swirl effect of primary stream has been observed. Thereafter, a sudden decrease of TKE occurs due to entrainment of subsonic secondary flow, followed by a gradual increase in constant area mixing tube. It increases again due to shock as observed in Figure 11 as second peak.

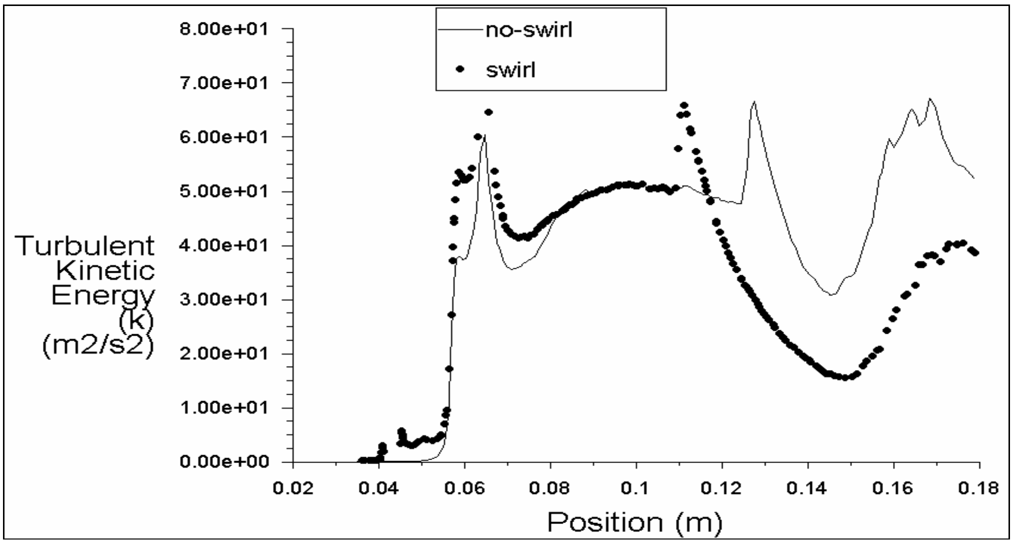


Figure 11: Turbulent kinetic energy variation for swirl and without swirl ejector

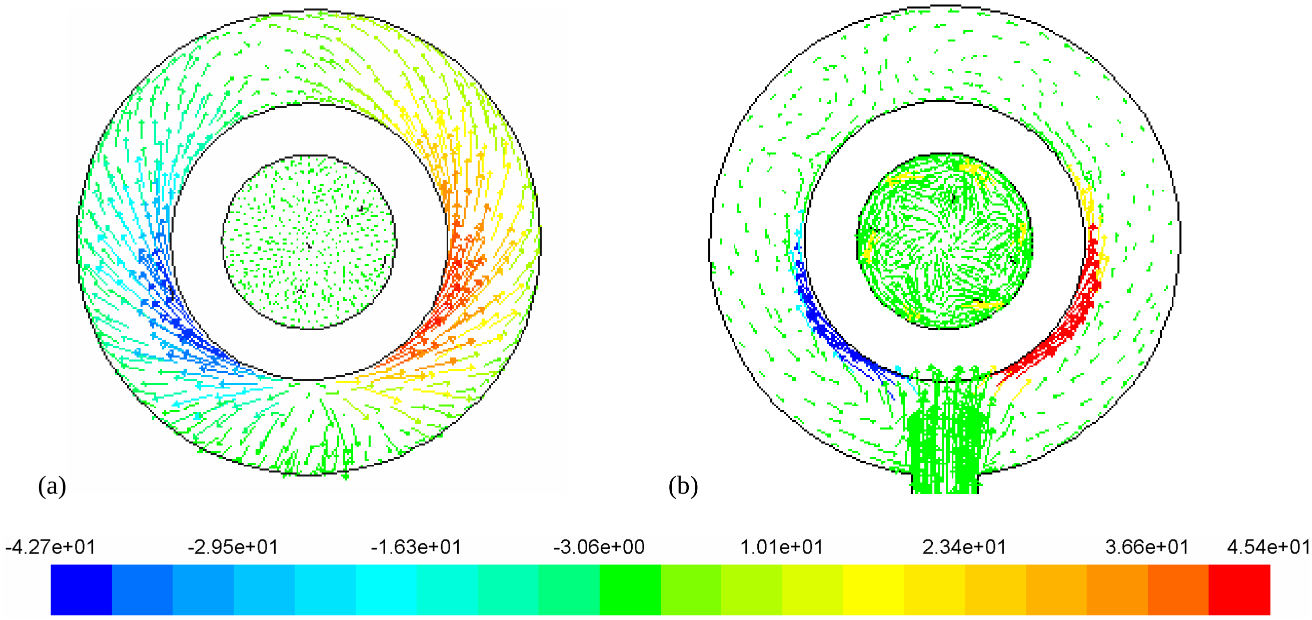


Figure 12: Radial distribution of tangential velocity (m/s) in the plane (a) before and (b) after the swirl generator

Radial distribution of tangential velocity in cross-sectional planes perpendicular to flow direction, before and after the swirl generator, has been shown in Figure 12. The swirling in the annular region of the planes is due to tangential entry of secondary stream into the ejector. The tangential vectors due to swirling effect of primary stream inside the inner circle of the planes are more pronounced in the plane situated after the swirl generator. The effect of condenser pressure on the entrainment ratio has been simulated and it has been observed from Figure 13 that entrainment ratio is constant for a range of condenser pressures representing double choking mode. It decreases with increase in condenser pressure which represents single choking mode operation. The condenser pressure at which the transition from double choking to single choking mode takes place represents critical condenser pressure.

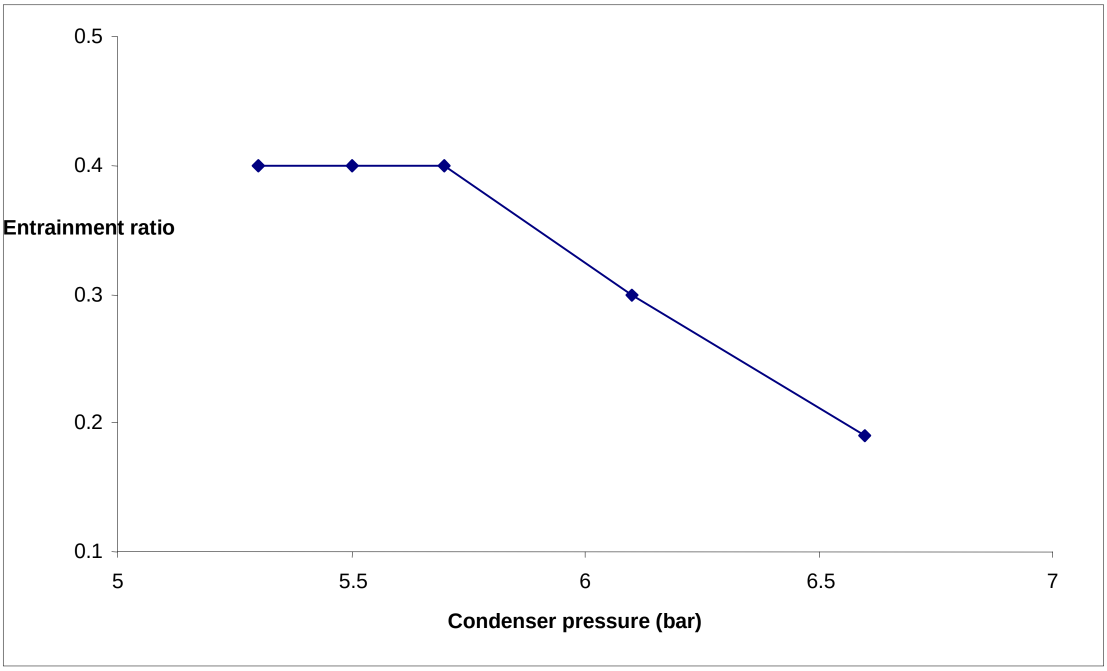


Figure 13: Effect of condenser pressure on entrainment ratio

Table 1: Entrainment ratio with mass flow rates of inlets and net mass flow rate

Ejector	Primary mass flow rate (kg/s)	Secondary mass flow rate (kg/s)	ER
Ejector without swirl	0.04832	0.0188	0.389
Ejector with swirl	0.04568	0.018894	0.414

From the Table 1 above, it is observed that for a low primary mass flow rate input, entrainment of secondary stream gets increased for ejector with swirl as compared to ejector without swirl. Increase in entrainment ratio has been observed to be about 6%.

5. CONCLUSIONS

VJR system has been studied with swirl effect to the primary stream for a set of operating conditions of an ejector using swirl generators. The swirl increases the contact time between the primary and secondary streams, resulting in better mixing of both the streams. This results into better exchange of momentum and enhanced entrainment performance, which in turn enhances the performance of whole VJR system. From the analysis the entrainment ratio has been observed to increase by about 6% as compared to the ejector without swirl.

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