Journal of Applied Fluid Mechanics, Vol. 11, No. 2, pp. 385-395, 2018.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
DOI: 10.29252/jafm.11.02.28141

Comparison of Flow Field Simulation of Liquid Ejector Pump using Standard K-ε and Embedded LES Turbulence Modelling Techniques

Q. Zaheer[1]† and J. Masud[2]

[1]*College of Aeronautical Engineering, NUST, Risalpur 24080, Pakistan*
[2]*Department of Mechanical and Aerospace Engineering, IAA, Air University, Islamabad 44000, Pakistan*

†*Corresponding Author Email: qasim1985@cae.nust.edu.pk*

(Received June 22, 2017; accepted October 21, 2017)

ABSTRACT

The flow field analysis of a liquid ejector pump is important for its design improvements, performance estimation and understanding of mixing and entrainment phenomenon. Ejector pumps, due to their simpler design and ease of maintenance are used in a variety of industrial applications. The subject pump, under consideration in this study, is used for transferring fuel from one fuel tank to another in a fighter aircraft. To study the underlying flow field characteristics of subject ejector pump, the fluid domain is simulated using Embedded LES turbulence modelling technique in Ansys Fluent ® environment. The flow field and performance parameters of subject pump are then compared with that of previously researched study of same pump wherein Standard K-ε RANS Turbulence Model was used. It is revealed that the results obtained using Embedded LES are much closer to experimental data than that of Standard K-ε. The limitations of RANS turbulence model for accurate simulation of complex flow field of subject pump are then identified, analyzed and discussed in details by studying the flow characteristics such as Reynolds shear stresses distribution, Potential Core estimation and turbulent viscosity modelling, obtained using both turbulent models.

Keywords: Ejector pump; Complex flow; Reynolds shear stresses; Potential core; Embedded LES.

NOMENCLATURE

ELES	Embedded Large Eddy Simulation	μ_t	turbulent Viscosity
SGS	Sub Grid Scale	k	turbulent kinetic energy
u’v’	Reynolds stresses	ε	dissipation rate
		ρ	fluid density
τ_{ij}	turbulent stresses	l_o	integral length scale

1. INTRODUCTION

Ejector pump is a device that transfers the momentum from a high velocity primary jet flow (motive flow) to the secondary flow (entrained flow). The ejector pumps are also referred as injectors or jet pumps. They can be operated with the compressible as well as incompressible fluids. When the ejectors are operated using incompressible fluids like liquids, they are often termed as Jet Pumps. One of the most important feature of these devices is that they provide the use of any ordinary centrifugal pump with a lower head but with a higher capacity, thus resulting into 2-3 folds increased mass flow rates. The geometry of ejector pump is very simple which provides pivotal advantages like ease of installation, economical usage, lack of moving parts, lubrication sealing problems etc. Due to these advantages, these pumps are extensively used in different industrial applications as well as in engineering field. In this study, the subject modeled ejector pump is being used in the fuel system of a fighter aircraft for transfer of between the fuel tanks.

The ejector pump flow domain is comprised of adverse pressure gradient, formation of turbulent structures due to Kelvin-Helmholtz instabilities in flow and existence of turbulent shear flows like mixing layer, free shear layer and turbulent jet flow. Such field in which various turbulent phenomena takes place is generally referred to as complex flow filed. The existence of such complex flow of the ejector pump makes it difficult to predict its actual performance analytically. Simplified analytical models were devised as initial design methodology of ejector pump, as mentioned in (Royal Aeronautical Society, December 1985) but these mathematical models incorporate various assumptions, hence the prediction of accurate efficiency and performance of subject pumps is compromised. Thus, experimentation is carried out to ascertain the performance and efficiency of subject pumps but this is not economically feasible solution. With the advancement in the field of Computational Fluid Dynamics, the flow field of ejector pump can be modelled numerically and selection of suitable turbulence modelling technique can bring the numerical results closer to the experimental results.

The literature survey indicates various studies conducted to analyze the flow field of ejector pump using different turbulence models. An insight into the ejector flow phenomena was obtained using computational and analytical tools and the results were compared via shadowgraph images of flow domain (Adrienne *et al*. 2015). Computationally, the flow field was simulated using k-ε RNG and k-ω SST models, and the results revealed that later turbulence model predicted the flow features more accurately. The performance characterization of "short" ejectors was conducted analytically and experimentally and it was concluded that proposed new ejector model for "short" ejectors can accurately predict its performance (Im and Song, 2015). Experimentally, Laser visualization technique was utilized to determine and analyze flow of air inside a supersonic ejector (Desevaux *et al*. 2004). In that research work, the phenomena of choking of flow was studied in details and experimental data was utilized to authenticate CFD results. The experimental methodology was also utilized to visualize the ejector pump flow field which was integrated with Pulsed Detonation Engine. The methodology helped in determining the equivalence ratio which effectively induce secondary flow (Hoke *et al*. 2002). The effect of different geometrical configurations of primary flow inlets on the turbulent flow regime of jets was investigated using Reynolds Stress Model and it was concluded that development of the triangular jets is stronger than others (Kim and Park, 2013).

To comprehend the mixing and entrainment mechanism inside the turbulent mixing region of ejector pump, it is necessary to accurately simulate the physics of turbulent structures as they are the prime factor for above mentioned phenomenon. The literature shows that turbulence models based on RANS technique have deficiencies in identification and visualization of these important flow features (Yodere *et al*. 2013) as vortical structures are transient in nature. On the other hand, LES based turbulence models are more suitable for visualization of such turbulent structures in complex flow region like that of ejector pump (Zaheer and Masud, 2017). The accurate estimation of turbulent viscosity in such complex flows is also important as pressure and velocity profiles are directly linked to flow viscosity. Here again, the RANS turbulence models lack accuracy in numerically replicating the flow characteristics (mass flow rate) (Masud and Imran, 2015) when the flow field inside the subject pump was simulated and analyzed using Standard K-ε family of turbulence models for closure. The simulated results once compared to the experimental test data showed an over predicted mass flow rate due to the complex nature of flow which is mostly pronounced by the turbulent shear and mixing layers. The study showed that to numerically replicate the experimental data, the model coefficients needed recalibration (Masud and Javed, 2007). Hence, a *priori* simulation of subject pump flow field was not obtained as the model constants were tweaked randomly.

In present study, flow domain of subject pump is first simulated and analyzed using Large Eddy Simulation based turbulence model and then comparison is carried out with the experimental data for validation of results. The underlying reasons behind why the performance of RANS turbulence models is much less uniform for complex flows, like the one of subject pump, are explored and analyzed by comparing the simulated flow field characteristics using LES and RANS based turbulence models.

2. TURBULENCE MODELING

As the performance of RANS based turbulence models for accurate flow characterization of complex flows is inadequate (Menter, 2011), hence the advantages of Large Eddy Simulation based models are explored in the present study. In LES based turbulence models, the turbulent kinetic energy associated with larger vortical structures of the flow is resolved and only small, isotropic and homogeneous eddies are modelled (Bouhanguel *et al*. 2015). But the high computational power requirement for performing LES based simulations makes it tedious and computationally inviable for engineering problems. Embedded LES, a hybrid RANS-LES turbulence model, is then utilized to overcome the computational cost barrier associated with LES but at the same time taking advantage of LES based models in region of interest i.e. high turbulence region is numerically solved using LES whereas rest of the flow field is solved numerically using Standard k–ε turbulence model. The proposed methodology is performed using ANSYS Fluent® (Cokljat *et al*. 2009).

Mathematical formulation of Standard K-ε turbulence model, which is based on transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε), is given as follows:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial\left(\rho \overline{u}_i k\right)}{\partial x_i}=-\rho\overline{u'_i u'_j}\frac{\partial \overline{u}_i}{\partial x_i}-\rho\varepsilon +\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] \quad (1)$$

and 'ε' is modeled as

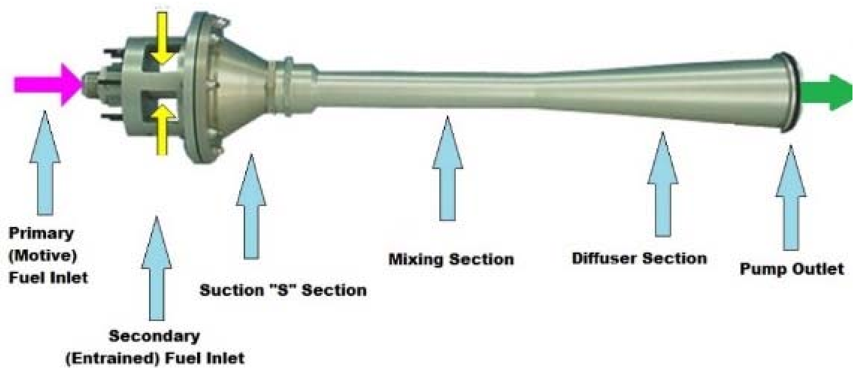


Fig. 1. Various sections of Ejector Pump.

Table 1 Geometrical features of ejector pump

Primary Nozzle (mm)		S- Sec Inlet Dia (mm)	Mixing Chamber Dia (mm)	Mixing Chamber Length (mm)	Diffuser Section Length (mm)	Pump Outlet Diameter (mm)
Inlet Dia	Exit Dia					
18	7	50	34	272	271	72

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial\left(\rho\overline{u_i}\,\epsilon\right)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j} + C_1\rho_k\frac{\varepsilon}{k}-C_2\rho\frac{\varepsilon^2}{k} \tag{2}$$

The eddy viscosity μ_t is expressed as:

$$\mu_t=\rho C_\mu L_t\sqrt{k}=\rho C_\mu\frac{k^2}{\varepsilon} \tag{3}$$

The constants carry the default values: $C_\mu=0.09$, $C_1=1.44$, $C_2=1.92$, $\sigma_k=1.0$ and $\sigma_\varepsilon=1.3$.

Utilizing the Kolmogorov theory of turbulent flows, Large Eddy Simulation based turbulence models explicitly solve the large eddies whereas implicitly solve for eddies of small sizes by incorporating sub grid-scale turbulence model. To decompose resolved and modelled field, a filtering function G is used which decomposes the subject field into a resolved and subgrid scale modeled parts. The function G is generally defined as:

$$\overline{u_i}(\vec{x})=\int G(\vec{x}-\vec{\epsilon})u(\vec{\epsilon})d(\vec{\epsilon}) \tag{4}$$

This result in

$$u_i=\overline{u_i}+u_i' \tag{5}$$

Here $\overline{u_\iota}$ is the resolved part of velocity vector where as $\acute{u}_\iota$ is modelled subgrid part. The filtering operator used in LES is the grid cell dimension (box filter), therefore the resolved length scales of turbulent flow filed can be estimated by knowing the maximum grid cell dimension. Once this filtering function is applied to Navier Stokes equations, it resulted in nonlinear advection terms.

$$\tau_{ij}=\overline{u_i}\,\overline{u_j}-\overline{u_i u_j} \tag{6}$$

To solve these turbulent stresses term, WALE subgrid scale model is used in the LES domain of the flow field. WALE model is based on Boussinesq hypothesis for calculation of SGS stress tensor.

3. GEOMETRICAL AND NUMERICAL SETUP

The under-investigation pump, being a component of aircraft fuel system, is immersed in fuel contained in the fuel tanks. To transfer this bulk of fuel from one tank to another, a high pressure, known as motive fuel, from fuel pump is injected into ejector pump through primary fuel nozzle. Once this stream of high velocity fuel is discharged from primary nozzle, it creates a low-pressure region in the near field of primary nozzle, hence entrains fuel from fuel tank via secondary nozzle. The pressure of bulk of fuel is thus increased once it flows out of the ejector pump due to momentum transfer between primary and secondary fluid streams. The different components of the subject ejector pump are displayed in the Fig. 1.

The geometrical details of subject pump are given in Table 1. The dimensions of subject pump are rendered into the CAD Model (3D) using Gambit® software and meshing is also carried out in the same software.

For analyzing the flow field using Embedded LES, the complete fluid domain of pump needs to be divided into RANS and LES zone where respective turbulence models can operate independently. The defined fluid zones and accompanying interfaces are displayed in Fig. 2. The placement of RANS-LES interfaces is such that they must lie in section of uninterrupted equilibrium. For conversion of modelled TKE from RANS zone to LES zone, Vortex Method is used to generate synthetic

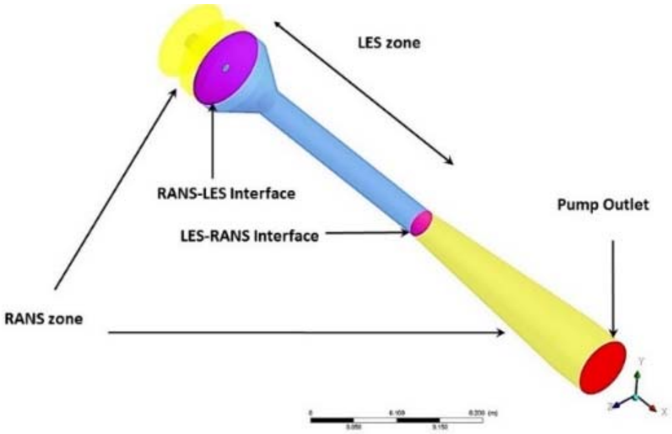


Fig. 2. CAD model of pump displaying fluid zones and interfaces.

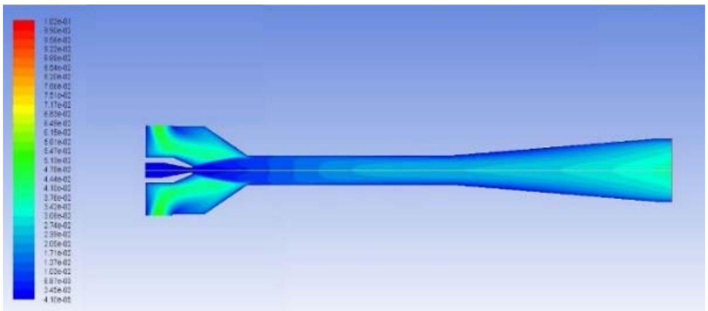


Fig. 3. Contours of ILS in LES zone.

turbulence at specified RANS-LES (Mathey *et al.* 2003) and no perturbation is generated synthetically at LES-RANS interface.

The quality of LES performed is highly dependent on fineness of the grid cells. From the Turbulent Kinetic Energy spectrum analysis, it is evident that approximately 80 % of total TKE is contained in eddies of integral length scales. Hence this length scale must be sufficiently resolved while simulating flow field using LES. By knowing the distribution of turbulent structures equivalent to dimensions of Integral Length Scale (ILS) inside the flow domain of pump, an estimation to maximum grid cell dimensions can be ascertained. The length scale (l_o) is given by the Eq. (7) and its distribution on the grid using a precursor RANS simulation is shown in Fig. 3.

$$l_o \sim \frac{k^{3/2}}{\varepsilon} \tag{7}$$

From Fig. 3, it is evident that a maximum cell dimension of $\mathbf{5 \times 10^{-4}}$ m may resolve the turbulent eddies of integral length scale. The structured mesh of 2.44 Mil in RANS and 9.8 Mil in LES zones is generated. The mesh details are shown in Fig. 4. The time step size of 5μsec is used to satisfy the CFL~1 requirement for LES. The properties of fuel (jet A-1) are used and it is treated as incompressible fluid. Pressure boundary conditions are used at primary nozzle inlet (three different settings), fuel tank inlet (hydrostatic pressure corresponding to fuel height above the ejector pump) and pump outlet (values corresponding to nozzle inlet pressures). The values are extracted from previously used test data (Masud and Javed, 2007).

4. RESULTS AND DISCUSSION

4.1. Quality Estimation of LES

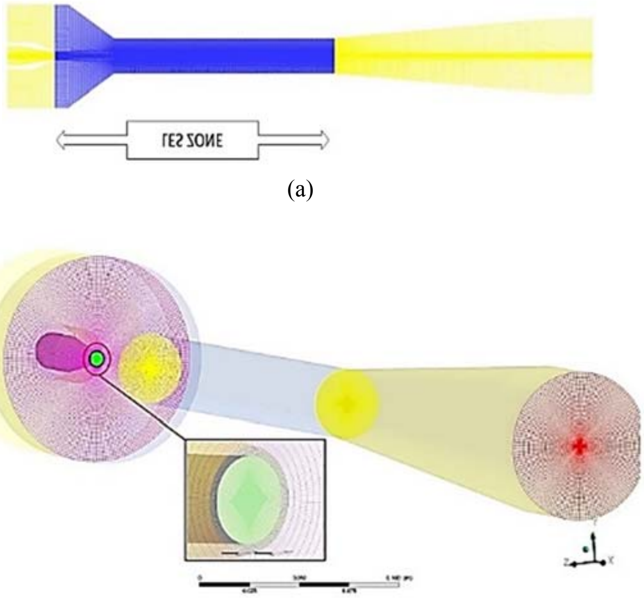
The quality of Large Eddy Simulation performed for analyzing the flow characteristics of subject ejector pump is assessed by following methods:

(i) Assessment of Grid Resolution

The qualitative analysis of LES which is embedded inside a global RANS domain, is carried out using methodology proposed by Celik *et al* (2005). The LES Index of Quality (LES IQ) compares the turbulent viscosity to that of laminar one using the following relation.

$$LES\ IQ_{\vartheta} = \frac{1}{1 + 0.05\left[\frac{\left(\mu + \mu_{sgs}\right)}{\mu}\right]^{0.53}} \tag{9}$$

The constant values used in the above-mentioned relation are calibrated such that index acts like the ratio of resolved to total turbulent kinetic energy. As it is a dimensionless number and varies from 0-1, the LES IQ greater than 0.8 is representation of a good LES whereas 0.95 and higher is referred as



(a)

(b)

Fig. 4. Mesh Details (a) X-sectional view (b) Isometric View at various cross sections of pump.

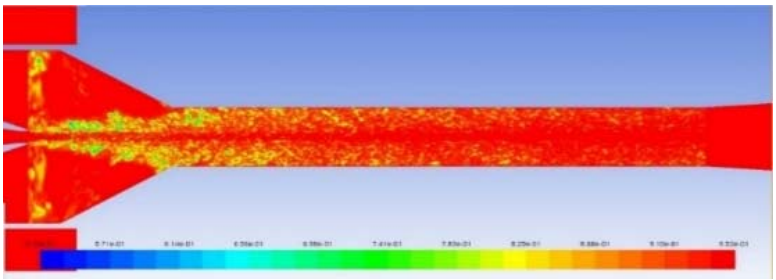


Fig. 5. LES quality index plot.

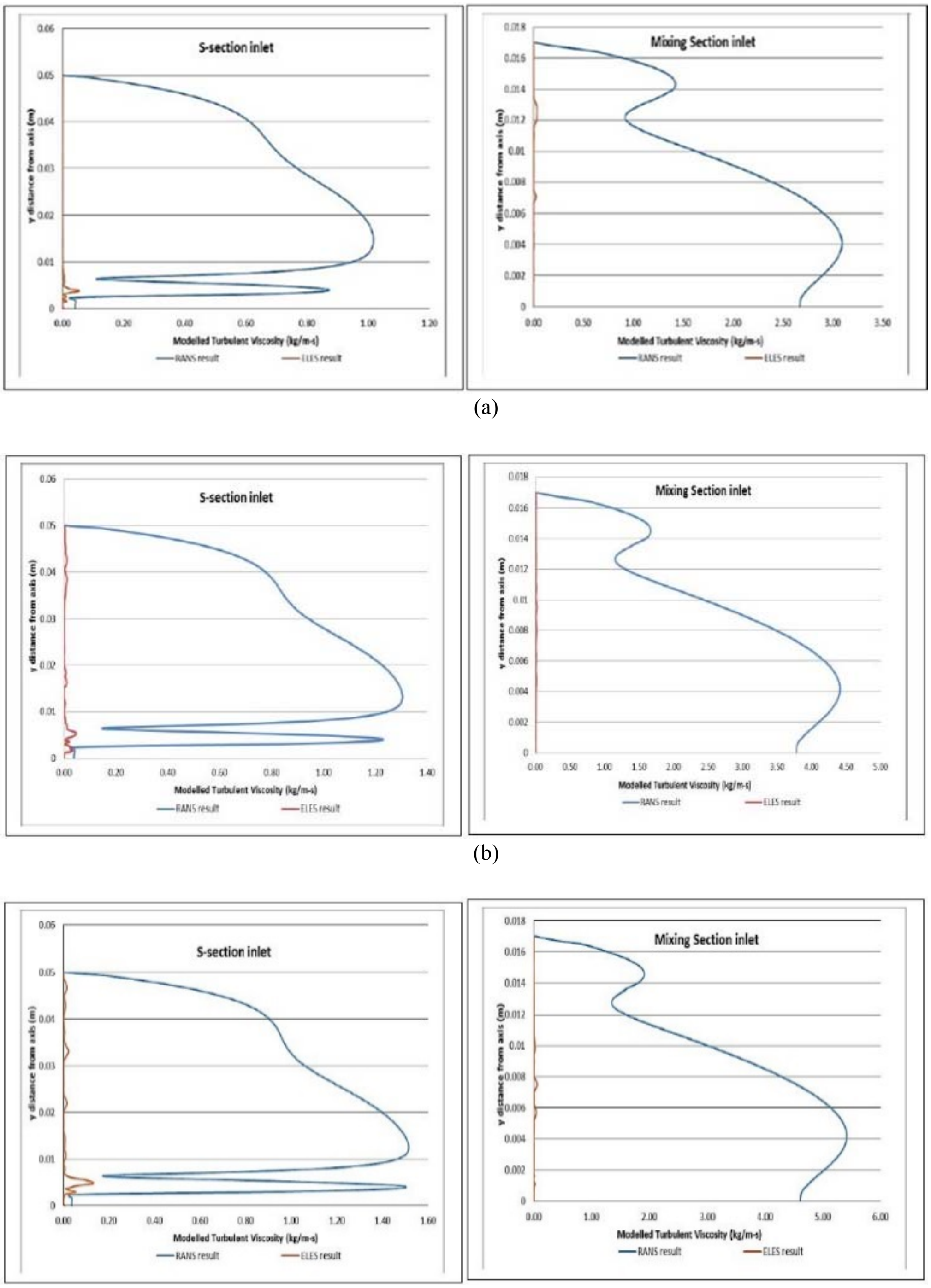
DNS (Celik *et al*. 2005). The distribution of index over LES zone inside flow domain of pump for one of the test cases, is shown in Fig. 5. It is apparent that sufficient grid resolution is incorporated, satisfying the laid down quality criteria for LES.

(ii) Eddy Viscosity Modeling

The other parameter for estimating the quality of LES is the extent of modeling of turbulent viscosity by the subgrid scale model. As per the literature, subgrid scale turbulent viscosity must be far lesser than that of RANS turbulence model and if the SGS viscosity completely vanishes then it is plausible to assume LES solution as DNS one. In Fig. 6, the modelled turbulent viscosity by WALE SGS model in case of LES and that of Standard k–ε RANS model, is compared at two different cross section of the ejector pump. The selected locations are the inlet of S section and the inlet of mixing section. It is clearly inferred from these plots that the modelled turbulent viscosity by WALE SGS model is far smaller than that of Standard k–ε RANS model, hence ascertaining the better quality of LES performed in this study.

4.2. Validation of Results

The matrix of the experimental data of subject ejector pump [9] includes the range of Primary Nozzle inlet pressure from 0.6 MPa to 2.0 MPa with the interval of 0.2 MPa. Out of this matrix, three test cases are selected i.e. primary nozzle inlet pressure of 0.6 MPa, 1.2 MPa and 1.8 MPa for numerical simulation of the flow field of ejector pump. The parameters of ejector pump flow field which are of paramount importance include pressures and mass flow rates at pump outlet, secondary flow inlet and primary nozzle inlet. The values of these parameters obtained after performing ELES numerical simulation of ejector pump flow field are then validated against the experimental results. The Standard k–ε simulation results from the previous study are also plotted, Fig. 7, depicting inadequacy of RANS turbulence model of reproducing experimental results. It is clearly inferred from the comparison that the results obtained from high fidelity Embedded LES are improved than RANS model with default values of constants used in its mathematical model. Hence the Embedded LES technique can be utilized to predict *a priori* simulation of the under-investigation pump flow field. It can be inferred from the Fig. 7 that with the default values of constants, the Standard k–ε RANS model accurately simulates the pressure at the boundaries of ejector pump but there is a variation in results with respect to experimental



(a)

(b)

(c)

Fig. 6. Comparison of modelled turbulent viscosity at primary nozzle pressures of (a) 0.6 MPa (b) 1.2 MPa (c) 1.8 MPa

values as far as mass flow rate prediction is concerned. The RANS turbulence model over predicts the mass flow rate at the ejector pump outlet. This deficiency of RANS model is overcome by the ELES simulation as the results for prediction of both pressures and mass flow rate are closer to the experimental values.

The performance parameters of the ejector pump like Mass Flow Ratio M, Pressure Ratio N and the efficiency η are also calculated based on the results obtained from Embedded LES simulation. These results are also validated against the experimental values, shown in Table 2 and found in better agreement. Hence the performance of pump is also validated.

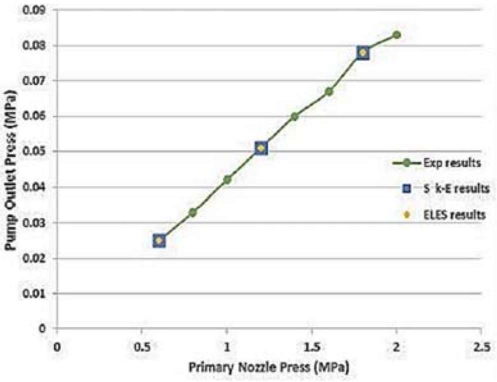
4.3. Flow Field Analysis Using Embedded LES

The static pressure profiles for three test cases are shown in Fig. 8. The generation of turbulent

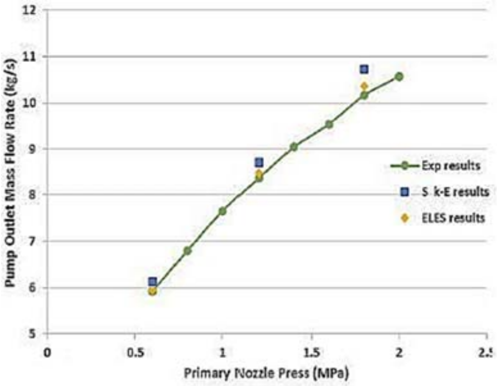
Table 2 Comparison of ejector pump performance parameters between Embedded LES & Experimental values

Inlet press(MPa)		Pump Outlet press (MPa)	Primary Nozzle MFR (Qp)		Secondary Nozzle MFR (Qs)		MFR ratio (M)		Ef (η)	
Pri Nozz	Sec Nozz		Exp	ELES	Exp	ELES	Exp	ELES	Exp	ELES
0.60	0.00224	0.025	1.17	1.15	4.76	4.79	4.06	4.16	0.161	0.164
1.20	0.00224	0.051	1.65	1.63	6.72	6.84	4.06	4.20	0.172	0.178
1.80	0.00224	0.078	1.98	1.98	8.17	8.37	4.12	4.23	0.181	0.185

structures at the primary nozzle exit is the reason for pulsating behavior of pressure along the flow path. The low-pressure region is the consequence of phenomenon of generation of turbulence (Aldas and Yapici, 2014) (Karimipanah, 1996). As the flow travels downstream, the primary and secondary flow streams get mixed and momentum exchange takes place which recovers the static pressure from negative peak. The static pressure is further increased to design outlet pressure in the diffuser section.



(a)



(b)

Fig. 7. Comparison of Exp, ELES and Standard K-ε results (a) Pump outlet pressure (b) Pump outlet Mass flow rate.

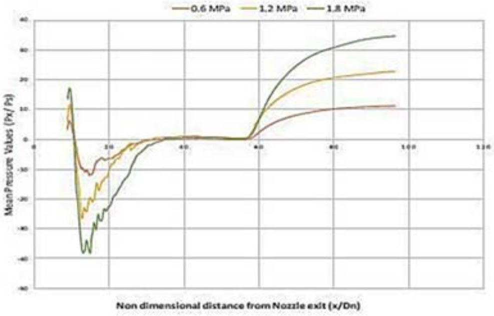
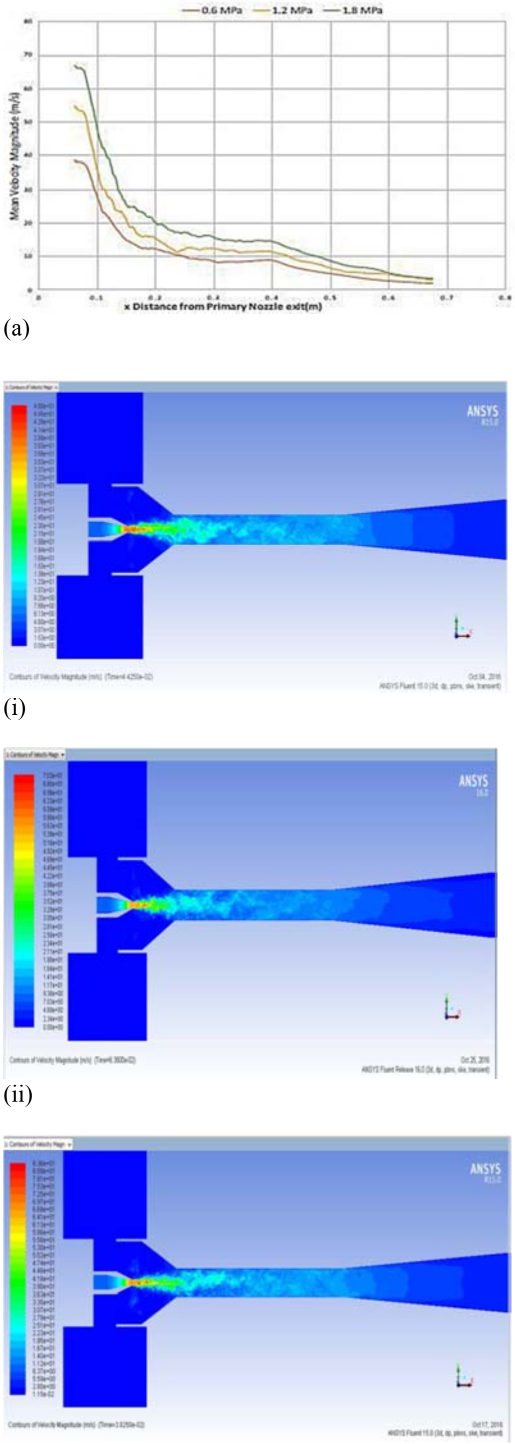


Fig. 8. Averaged Static Pressure profile.

The velocity variation along the centerline of pump is depicted in Fig. 9. The high-speed flow ejects from exit of primary nozzle and discharges into the domain of relatively static flow. As this high velocity flow encounters fluid from secondary nozzle, it transfers its momentum to the later one, consequently, its velocity reduces. The distance downstream of primary nozzle where the velocity almost remains unchanged is called the “potential core”. This region of uniform flow vanishes because of spreading of shear layers. The mixing of jet flow is characterized by the decrease of the centerline velocity after potential core.

The mixing and entrainment phenomenon of ejector pump fluid streams can be accurately computed by analyzing the distribution of TKE across flow domain. The profile of Tubulent Kinetic Energy, Fig. 10, shows where the kinetic energy of turbulent structures is low, the region is more pronounced by less turbulence and alongcenterline, it is the region where potential core exists. Once the uniform velocity region culminates on the centreline, the kinetic energy of vortices increases, thereby increasing the the mixing and entrainment between the two fluid streams. The crest of Turbulent KE profile lies in the region where shear layers, initiated from the lip of primary nozzle, meet each other. The dissipation of TKE takes place as momentum exchange between secondary and primary fluid streams reaches equillibrium state. The shedding of larger eddies into realtively smaller eddies decreases the magnitude of TKE further downstream until it vanishes out.



(a)

(i)

(ii)

(iii)

(b)

Fig. 9. (a) Variation of Averaged Velocity Profile (b) Instantaneous Velocity Contours for primary nozzle pressures of (i)0.6 MPa (ii)1.2 MPa (iii) 1.8 Mpa.

In to visualize the tubulent structures present in the flow domain of ejector pump, iso contours of Q-criterion are plotted for each case and are coloured with instantaneous velocity. The plots are shown in Fig. 11. The turbulent structures at the exit of the primary nozzle are indicative shear layer generation and hence mixing process. The phenomenon of vortex shedding is also visible as the large vortical structures break down to the smaller ones as the fluid flows downstream. Such visualization cannot be achieved from RANS based models.

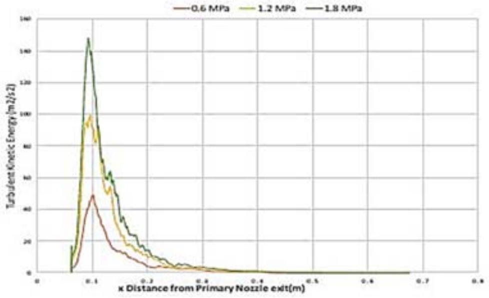
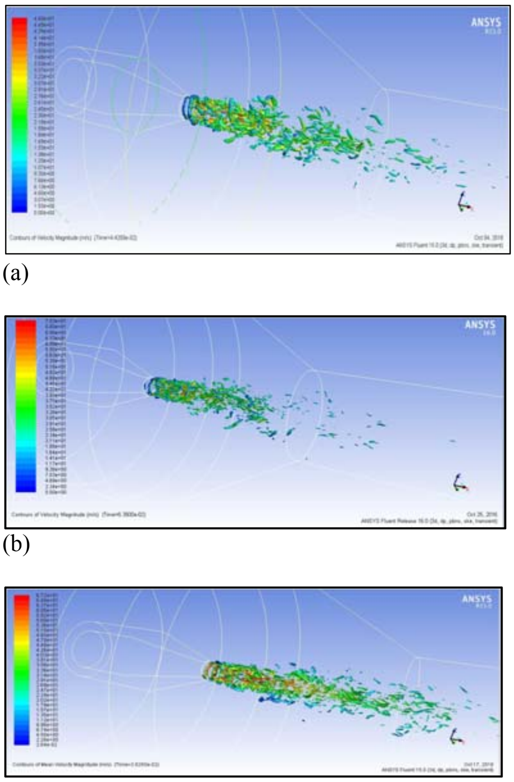


Fig. 10. Variation of TKE along flow direction.



(a)

(b)

(c)

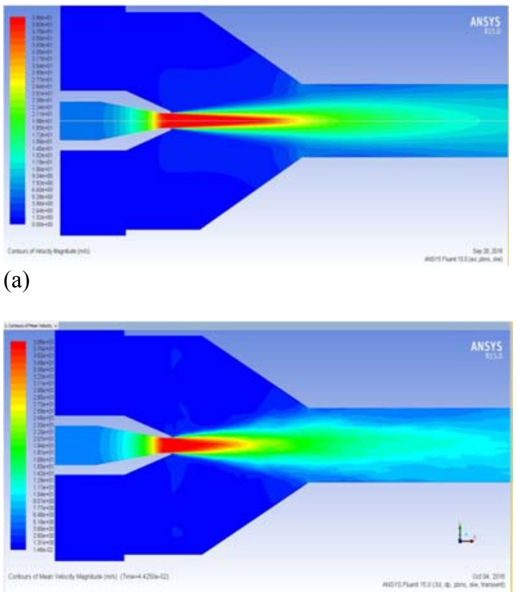
Fig. 11. Iso contours of Q-criterion colored by mean velocity magnitudes at primary nozzle pressures of (a) 0.6 MPa (b) 1.2 MPa (c) 1.8 Mpa.

4.4. Comparison of Ejector Flow Characteristics : Embedded LES vs Standard K-ε

The previous research work (Masud and Imran, 2015) (Masud and Javed, 2007) on utilizing the RANS turbulence models and selecting the best for reproducing the experimental results related to the flow field of subject ejector pump suggests that with the default values of constants used in the mathematical modelling of RANS turbulence models, they are inadequate to reproduce the experimental mass flow rates. To identify the reasoning behind lack of accuracy of Standard k–ε RANS turbulence model for prediction of complex flow fields, a comparison of flow characteristics obtained from Standard k–ε and Embedded LES simulations of ejector pump flow field, is drawn. As it is evident that the behavior / trend of flow field of ejector pump is somewhat similar in all three test cases, hence the flow field of only first test case i.e. of primary nozzle pressure of 0.6 MPa, is chosen for comparison purpose.

(i) Comparison of Potential Core length

To compare the potential core length of subject ejector pump, the unsteady statistics of the instantaneous velocity field simulated by Embedded LES are gathered for a sufficient flow through time. The mean velocity contours are then plotted on the cross-sectional view of ejector pump domain. These results are then compared with that of Standard k–ε simulation. The contour plots, Fig. 12, and mean velocity profile plot, Fig. 13, reveal that RANS based simulation overpredict the length of potential core as compared to that of Embedded LES.



(a)

(b)

Fig. 12. Comparison of Potential Core prediction (a) Standard k–ε (b) Embedded LES.

The reason behind this deficiency of Standard k–ε RANS model is that it underpredict the initial shear layer growth rate. The turbulent structures in near field of jet region, at the end of potential core and farther downstream are different from each other due to flow physics. Hence, each region would require separate calibration of model constants, however, this has not been the case and a single set of Standard k–ε model constants are used whose calibration is based on fully turbulent flow. Therefore, the turbulence level of eddies is reduced which slows the shear layer growth rate throughout the flow field. This poor performance of RANS model results in weak mixing in shear layers of jet, yielding potential core length that are longer than the Embedded LES simulation. As the shear layer growth rate is largely influenced by structural details of large coherent structures, the Embedded LES directly resolves the large turbulent coherent structures through the use of unsteady Navier Stokes equations and hence accurate simulation of potential core length.

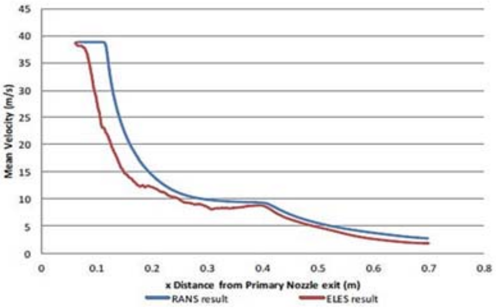


Fig. 13. Comparison of Averaged Velocity Profile.

(ii) Comparison of Jet Flow Spread Rate

For the prediction of primary jet flow spread rate, the mean velocity profile obtained from Embedded LES and RANS models are plotted at two different cross sections i.e inlet of S section and inlet of Mixing Section, Fig. 14. It is very much evident from these plots that as the primary flow jet ejects out of primary nozzle exit and flows downstream, its outward spread into the secondary fluid due to generation of shear layers and consequent turbulent structures, is strongly underpredicted by Standard k–ε RANS model than that of Embedded LES. A similar deficiency is also observed by (S. Kubacki *et al.* 2010),(Surya *et al.* 2017) and (Fernandez *et al.* 2007). Following are the mean velocity profiles at said cross sections of ejector pump.

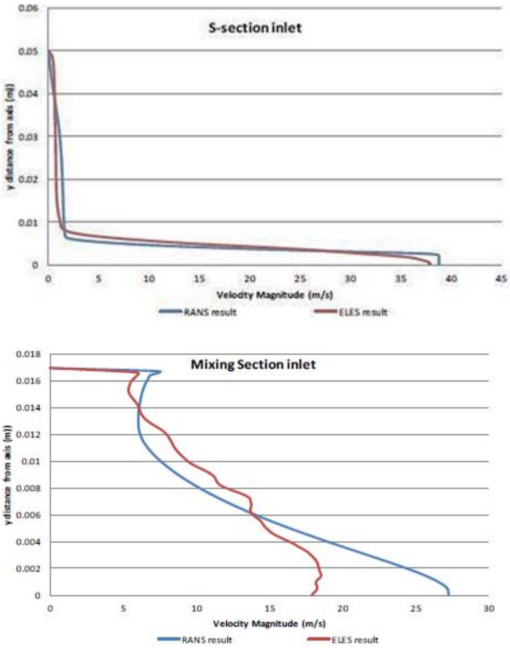


Fig. 14. Comparison of average velocity profiles at two sections of ejector pump.

The underprediction of primary jet spread rate by Standard k–ε RANS model is due to the false prediction of Reynolds shear stresses (u'v') close to the symmetry plane and in shear layers of jet. The quantitative measure of the Reynolds shear stresses represents the transports of momenta by coherent structures' motion. The evaluation of these stresses help in estimating of momentum being transported by the coherent turbulent structures between the primary and secondary flows. The quantitative analysis of these Reynolds shear stresses at defined cross section of ejector pump, Fig. 15, explains that momentum transfer between the primary and secondary fluids is underpredicted by Standard k–ε RANS model as compared to that of Embedded LES. Due to this deficiency of Standard k–ε RANS model, the jet spread rate is also underpredicted and hence the numerically simulated mass flow rate at the pump outlet is overpredicted than the corresponding experimental value.

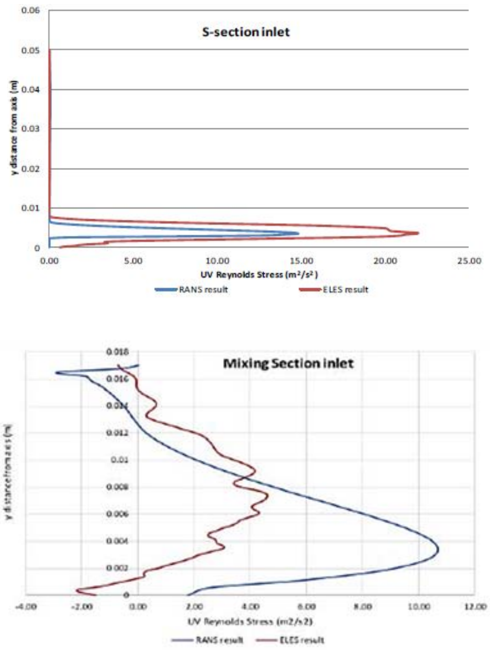


Fig. 15. Comparison of (u'v') Reynolds Shear Stress profiles at two cross sections of ejector pump.

5. CONCLUSION

The analysis of comparison of turbulent flow characteristics between the Standard k–ε RANS model and Embedded LES simulations of ejector pump flow field reveals a strong deficiency in Standard k–ε model for simulating the complex flow fields. This deficiency of said model is due to its reliance on Boussinesq Approximation for modeling of eddy viscosity μ_t. The Standard k–ε RANS model constants are calibrated for spreading rate of jets in fully developed region and as this model is based on eddy viscosity, it does not possess enough freedom to calibrate itself for non-homogenous, anisotropic region of the flow domain. As in case of ejector pump flow field, the primary region of interest is the flow developing region located in the nearfield of primary nozzle exit where the turbulence is in non-equilibrium state. The Standard k–ε RANS model fails to accurately model this developing region of the flow. However, the same region is resolved in Embedded LES simulation to the extent of integral length scale of turbulent spectrum present in ejector pump flow field. Hence, the results obtained are in better approximation to the experimental data. Therefore, it is concluded that LES based turbulence models can be used as a priori to estimate ejector pump performance characteristics.

REFERENCES

Adrienne, B., Y. Bartosiewicz and G. Sirinivas (2015). Visualization and Validation of Ejector Flow Field with Computaional and First-Principles Analysis, *Journal of Fluid Engineering* 137(5), 051107.

Aldas, K. and R. Yapici (2014). Investigation of effects of scale and surface roughness on efficiency of water jet pumps using CFD, *Engineering Applications of Computational Fluid Mechanics* 8(1), 14-25.

Bouhanguel, A., P. Desevaux and E. Gavignet (2015). Visualization of flow instabilities in supersonic ejectors using Large Eddy Simulation, *Journal of Visualization*.

Celik, I., Z. Cehreli and I. Yavuz (2005). Index of resolution quality for large eddy simulations, *Journal of Fluids Engineering* 51(27), 949–958.

Cokljat, D., D. Caradi, G. Link, R. Lechner and F. Menter (2009). Embedded LES Methodology for General Purpose CFD Solvers, in *6th Int. Symp. Turbulence and Shear Flow Phenomena*,, Seoul, Korea.

Dennis, A. Y. *et al* (2013). Modeling of Turbulent Free Shear Flows, in *43rd Fluid Dynamics Conference and Exhibit AIAA*, San Diego, California.

Desevaux, P., A. Mellal and Y. A. d. Sousa (2004) Visualization of Secondary Flow Choking Phenomena in a Supersonic Air Ejector," *Journal of Visualization* 249-256.

Fernandez, J., J. Elicer Cortes, A. Valencia, M. Pavageau and S. Gupta (2007). Comparison of low-cost two-equation turbulence models for prediction of flow dynamics in twin-jets devices,, *Int. Comm. Heat Mass Transfer* 34, 570–578.

Hoke, J., R. Bradley, J. Stutrud and F. Schauer (2002). Integration Of A Pulsed Detonation Engine With An Ejector Pump And With A Turbocharger As Methods To Self-Aspirate, in *40th AIAA Aerospace Sciences Meeting & Exhibit*, Reno, NV.

Im, J. H. and S. J. Song (2015). Mixing and Entrainment Characteristics in Circular Short Ejectors, *Journal of Fluids Engineering*

137(5), 051103.

Kubacki, S., J. Rokick and E. Dick (2010). Hybrid RANS/LES computation of plane impinging jet flow, in *19th Polish National Fluid Dynamics Conference (KKMP)*, Poznań.

Karimipanah, T. (1996). Turbulent jets in confined spaces, Centre for Built Environment, Royal Institute of Technology, Sweden.

Kim, W. H. and T. S. Park (2013). Effects of Noncircular Inlet on the flow structures in Turbulent Jets, *Journal of Applied Mathematics and Physics* 1, 37-42.

Masud and M. Imran (2015). Turbulence Modeling for Realistic Computation of Internal Flow in Liquid Ejector Pumps, in *53rd AIAA Aerospace Sciences Meeting*.

Masud, J. and A. Javed (2007). Modification of Standard K-ε Turbulence Model for Analysis and Design Refinement of Fuel Ejector Pump, in *45th AIAA Aerospace Sciences Meeting* , Nevada, USA.

Mathey, F. D. Cokljat, J. Bertoglio and E. Sergent (2003). Specification of LES Inlet Boundary Condition Using Vortex Method, in *4th International Symposium on Turbulence, Heat and Mass Transfer*, Antalya.

Menter, F. (2011). Turbulence Modeling for Engineering Flows, *ANSYS, INC*.

Royal Aeronautical Society (1985). Ejector and jet pumps - Design and Performance for incompressible liquid flow.

Surya, ***et al.*** (2017). CFD Simulation of Ejector in Steam Jet Refrigeration, *Journal of Applied Mechanical Eng*.

Zaheer, Q., J. Masud (2017). Visualization of flow field of a liquid ejector pump using embedded LES methodology., *Journal of Visualization* 20(4), 777–788.