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Thermal Analysis of Steam Ejector Using CFD

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ABSTRACT: This work focuses on the numerical simulation of the working of a steam ejector in order improve the performance. Computational Fluid Dynamics (CFD) was employed for the numerical simulation. In this work the effect of operating conditions on the performance of the steam ejector operating in conjunction with an ejector refrigeration cycle was considered along with the effect of geometry parameter. The model and meshing is done with GAMBIT and FLUENT solver is used for the analysis. The simulations are performed with different operating conditions and geometries. The entrainment ratio is found to increase with the decrease of boiler saturation temperature for the same condition of superheat, evaporator temperature and condenser pressure. The entrainment ratio is also found to increase with increase of evaporator temperature keeping the boiler temperature and condenser pressure constant. The entrainment ratio does not vary much with the condenser pressure until the critical condenser pressure. It is also found that the entrainment ratio increases with decrease of throat diameter of the primary nozzle. The increase of entrainment ratio can be found out from the moving downwards of the effective position. But, a larger mass of secondary fluid causes the momentum of the mixed stream to decrease. The decrease of momentum can be determined from the moving upstream of the shocking position. The movement of shocking position upstream can cause the ejector to operate at a lower critical condenser pressure.

KEYWORDS: Symmetric model, Ejector, Entrainment ratio, Throat diameter, Condenser pressure.

I. INTRODUCTION

A steam ejector is a device which utilizes the momentum of a high- velocity primary jet of vapour to entrain and accelerate a medium in still or at a low speed.The important functions of an ejector include maintaining vacuum in evaporation, removing air from condensers as a vacuum pump, augmenting thrust, and increasing vapour pressure as a thermal compressor. The thermal compressor is a steam ejector, but it utilizes the thermal energy to augment the performance by reducing the size of a conventional multi-stage evaporator. The steam ejector was introduced as an engineering device in the early 20th century. At the same time, researchers started to investigate its working mechanism. Keenan and Neumann [1] presented the first comprehensive theoretical and experimental analysis of the ejector problem. Xianchang Li et al. [2] carried out a numerical analysis to study about the influence of geometric arrangement on the performance of steam ejector used in conjunction with a steam evaporator. It is observed that any downstream resistance will seriously impede the suction flow rate. In addition, the entrainment ratio is sensitive to the location of the jet exit, and there is an optimum location where the primary flow should be issued. Tony Utomo et al. [3] in their study the use of steam ejector in desalination system, particularly multi effect desalination (MED) system. In this study, CFD (computational fluid dynamics) analysis based on the finite volume method was employed to investigate the influence of angle of converging duct on the ejector performance. Hisham El-Dessouky et al. [4] studied using semi-empirical models design and rating of steam jet ejectors. The model gives the entrainment ratio as a function of the expansion ratio and the pressures of the entrained vapour, motive steam and compressed vapour. E.D. Rogdakis et al. [5] discusses the behaviour of ammonia (R-717) through an ejector operating in an airconditioning system with a low temperature thermal source. The influence of three major parameters: generator, condenser and

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evaporator temperature, on ejector efficiency and coefficient of performance is discussed. Narmine H. Aly et al.[6] studied a computer simulation model for steam jet ejectors. The model was developed by application of the equations of continuity, momentum and energy to individual operation of nozzle, mixing chamber and diffuser. B.J. Huang et al. [7] studied, two empirical correlations from the test results of 15 ejectors are derived for the performance prediction of ejectors using R141b as the working fluid. Kanjanapon Chunnanond et al. [8] studied the methods to increase the efficiency of an ejector refrigerator, a better understanding of the flow and the mixing through an ejector is needed. Shengqiang Shen et al. [9] studied a new configuration of a bi-ejector refrigeration system. The purpose of one is to suck refrigerant vapour from the evaporator and discharge to the condenser; the other acts as a jet pump to pump liquid refrigerant from the condenser to the generator. Y. Bartosiewicz et al. [10] studied numerical results of a supersonic ejector for refrigeration applications. E. Rusly et al. [11] modelled ejector designs using finite volume CFD techniques to resolve the flow dynamics in the ejectors. Szabolcs Varga et al. [12] studied about factors influencing the performance of an ejector. In this work, three geometrical factors – the area ratio between the nozzle and constant area section, nozzle exit position and constant area section length were considered.

This work tries to analyse the performance of a steam ejector working in conjunction with a refrigeration cycle. The operating conditions which are considered for the analyses are (i) varying the boiler temperature with constant superheat, evaporator temperature and condenser pressures, (ii) varying the evaporator temperature with constant boiler temperature and condenser pressures, (iii) varying the condenser pressure with constant boiler temperature and evaporator temperature and (iv) also three different geometry of primary nozzle are considered, corresponding steam ejector geometry model is created and meshed.The three different geometries are analyzed at the same inlet and outlet conditions. The analysis results are compared with the experimental data given in ref [8]. The results obtained from the CFD analysis can be used to study about the effective position, expansion angle and shocking position in the steam ejector. The operating conditions which were employed for the analysis ranges from boiler temperatures 120 ^{0}C to 140 ^{0}C, evaporator temperatures are 5 ^{0}C–15^{0}C, and condenser pressures are 25 to 45 mbar.

Paper is organized as follows. Section II describes CFD simulation of the steam ejector. The processing is discussed in section III the results and discussions are in Section IV. Section V presents conclusions drawn from the present work.

II. CFD SIMULATION OF THE STEAM EJECTOR

The dimension of the ejector which is used for the analysis is considered from the Ref[8] and is shown in Fig. 1 and the three different primary nozzle dimensions (Fig.2) which are used for the analysis is given in table1. The detailed dimensions of steam ejector is used to build the geometry in Gambit software. The other important dimensions for creating the geometry were assumed: Suction inlet diameter = 49.2mm, Ejector outlet diameter = 40mm, Length of straight cross section after the diffuser = 20mm. The steam ejector model was developed using GAMBIT 2.4.6 software. Three 2-D Axi Symmetrical model was created according to the three primary nozzle dimension specified The model is then meshed using GAMBIT and the mesh near to the wall was refined using boundary layer meshing is given in Fig. 3.

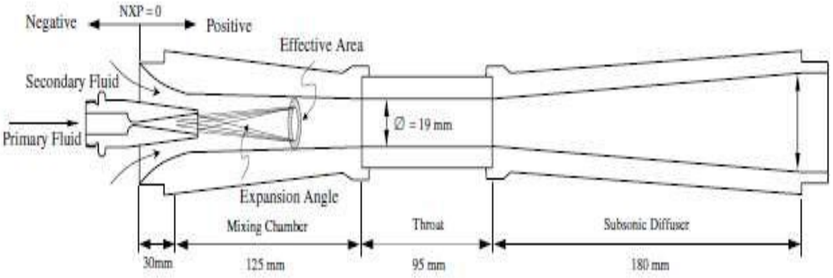


Fig.1 Steam ejector dimensions from Ref [8]

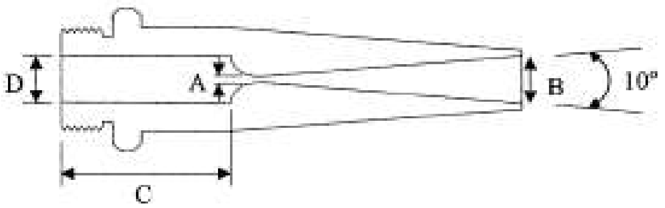
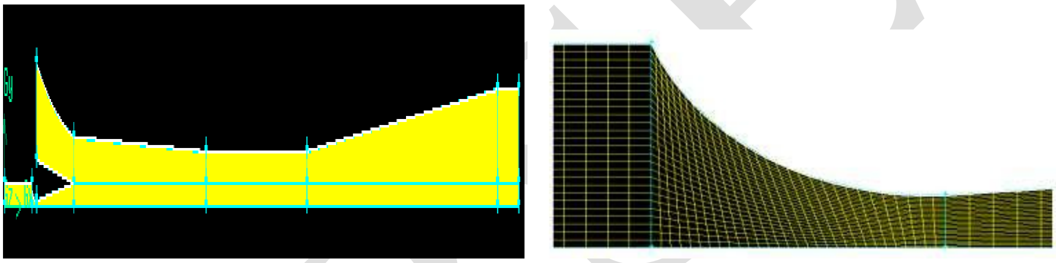


Fig.2 Primary nozzle dimensions

Table1. Primary nozzle dimensions

Nozzle no.	Geometry, mm			
	A	B	C	D
1	2.00	8.00	25.70	7.75
2	1.75	7.00	25.70	7.75
3	0.50	6.00	25.70	7.75



a. Geometric model

b. Meshed model

Fig.3 The geometric and meshed model of steam ejector

The primary inlet and secondary inlet were taken as pressure inlet and the ejector outlet was taken as pressure outlet. The axis was defined as the axis boundary type. And the wall boundary type was used to define the entire outer geometry. The boundary conditions employed to compare the performance of the three different geometries are for Primary inlet: Boiler temperature is 130^{0}C at 232.23 kPa and the secondary inlet the evaporator temperature is 5^{0}C at 800 Pa and the ejector outlet the condenser pressure is 35 mbar. Further the different operating conditions employed to compare the performance of the steam ejector are: a) Effect of condenser pressure, b) Effect of boiler temperature and c) Effect of evaporator temperature.

a) Effect of condenser pressure: The boundary conditions used for this analysis are at the primary inlet the boiler temperature is 130 ^{0}C at 232.23 kPa, at the secondary inlet the evaporator temperature is 10^{0}C at 1200 Pa and at the Ejector outlet three different cases of condenser pressure are considered 25 mbar, 35 mbar and 45mbar. b) Effect of boiler temperature: The boundary conditions used for this analysis are at the primary inlet three different cases of boiler temperature are considered 120^{0}C, 130^{0}C and 140^{0}C respectively at 169.18 kPa, 232.23 kPa and 313.22 kPa., at the secondary inlet the evaporator temperature is 15^{0}C at 1700 Pa and at the ejector outlet the condenser pressure of 45 mbar. c) Effect of evaporator temperature: The boundary conditions used for this analysis are at the primary inlet the boiler temperature is 120^{0}C at 169.18 kPa, at the secondary inlet the three different cases of evaporator temperature are considered 5^{0}C, 10^{0}C and 15^{0}C respectively at 800 Pa, 1200 Pa and 1700 Pa and at the Ejector outlet the condenser pressure of 25 mbar.

III. PROCESSING

The analysis was carried out in the commercial CFD package named FLUENT software. The geometry and grid system were imported to the solver FLUENT 6.3.26. The wall was set to be a stationary, non-slip wall. The fluid in the domain was set to be water vapour properties being constant. A pressure-based was used for all calculation cases. The "2-D axi-symmetric" model was adopted as the spatial approach. The fluid flow was set as steady state. Though Reynolds number could be low in certain areas, the flow is generally turbulent in the computational domain. Spalart-Allmaras turbulence model, with "Vorticity" as eddy generation method, was employed for all calculations. Energy equation was enabled. The convergence criteria used for the analysis were: Continuity: 1e-05 X-velocity, 1e-06,Y-velocity, 1e-06, Energy: 1e-06 Nut: 1e-04,Once the properties were evaluated, the data points were written in a file . The properties for fluid and solid are given in table 2 represents the domain considered as aluminium and flow is fluid properties are mentioned for the analysis.

Table2. The properties of fluid and aluminium

Property	Fluid	Aluminium
Density, kg/m^3	1.225	2719
Specific Heat(Cp), j/kg-k	1006.43	871
Thermal Conductivity, w/m-k	0.0242	180
Viscosity, kg/m-s	1.7894e-05	-
Molecular Weight, kg/kgmol	28.966	-

IV. RESULTS AND DISCUSSIONS

The numerical analysis was designed to investigate the changing of the static pressure through the ejector axis when the parameters affecting the ejector performance were varied. The operating conditions which are considered for the analysis are 1) varying the boiler temperature with constant superheat, evaporator temperature and condenser pressures; 2) varying the evaporator temperature with constant boiler temperature and condenser pressures; 3) varying the condenser pressure with constant boiler temperature and evaporator temperature. Also three different geometry of primary nozzle are considered, corresponding steam ejector geometry model is created and meshed. The three different geometries are analyzed at the same inlet and outlet conditions. The analyzed results provide a better understanding in the working characteristics of a steam ejector. This section gives the conformity of results obtained with the experimental results. FLUENT which solves the governing conservation equations of fluid flow by finite volume formulation. It is well known that all the turbulence models currently available have their own credibility and limitations.

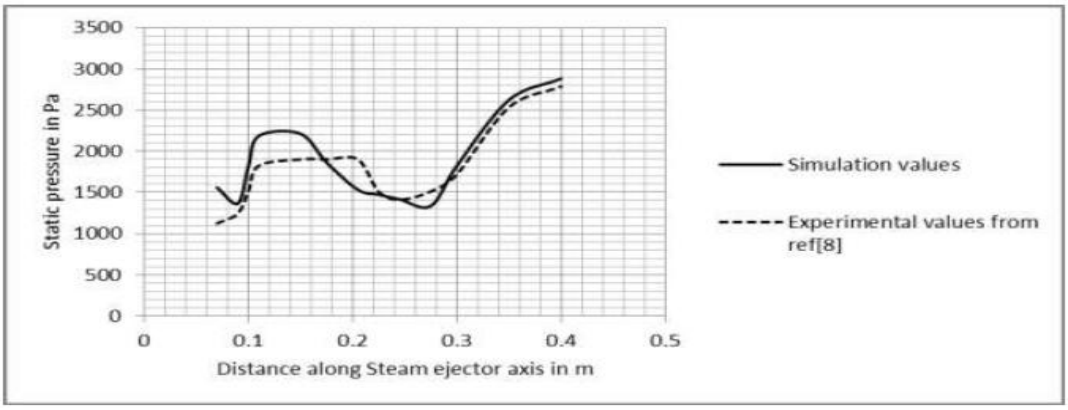


Fig4: Comparison of simulated result with experimental result for validation

Fig.4 gives the simulation values and experimental values plotted simultaneously in order to study the variation between them. The three different geometries are analyzed at the same inlet and outlet conditions. It is observed that the experimental and simulated results are very close. Fig5. Shows the variation of static pressure for the three different boiler temperatures are considered. The level of superheat, the condenser pressure was set as 30 mbar and evaporator temperature was kept constant at 10^0C for each case. The values of Entrainment Ratio(ER) for the three different boiler saturation pressure cases were calculated. The values are found to decrease with rise in boiler saturation pressure. This is due to the reason that the lower saturation pressure resulted in a smaller mass of steam leaving the primary nozzle with less velocity. This resulted in an expanded wave to fan out with smaller momentum and thus smaller expansion angle.

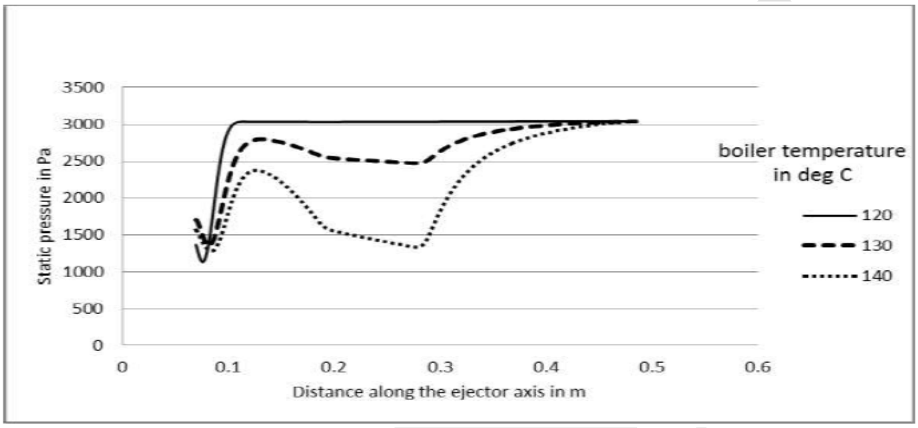


Fig.5: Static pressure profile along ejector, effect of boiler temperature

This caused a longer and larger entrained duct which resulted in the increase of entrainment ratio. The variation of Mach number of flow for the three different cases is also plotted, and is as shown in Fig.6. From the figure it is observed that Entrainment ratio is defined as the mass flow rate ratio of secondary to primary fluid. Entrainment ratio was calculated based on the stream function; according to definition of stream function the difference of two stream function will give the amount of flow through it. This principle is used to calculate the entrainment ratio. The boiler temperature varies the behaviour of mach number is similar in all cases

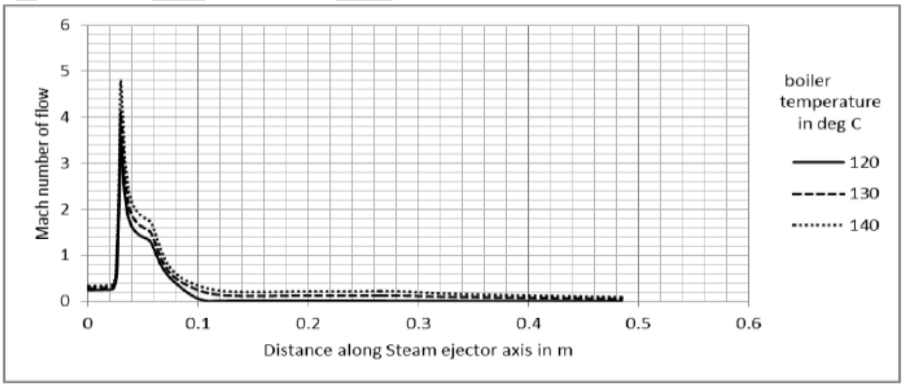


Fig.6: Mach number along ejector, effect of boiler temperature

Fig.7 shows the variation of static pressure for the three different cases of condenser pressure considered. The boiler temperature was set as 130^0C and evaporator temperature was kept constant at 10^0C for each case. It was seen that the change in entrainment ratio for the three cases considered were negligible. It can be inferred that the entrainment ratio is not affected by the condenser pressure. Another important inference from the figure 7 is that the shocking position moves back as the condenser pressure increases. And this might cause disturbance to the mixing and entrainment process if it is further increased. Fig.8 shows the variation of static pressure for the three different cases of evaporator temperature considered. The boiler temperature was set as 130^{0}C and condenser pressure was kept constant at 40 mbar for each case. It was seen that the entrainment ratio increases with increase in evaporator temperature. This is due to the movement of effective position to downstream with an increasingly higher evaporator temperature. The resultant longer entrained duct can handle higher amounts of secondary fluid which increases the entrainment and coefficient of performance of the refrigeration.

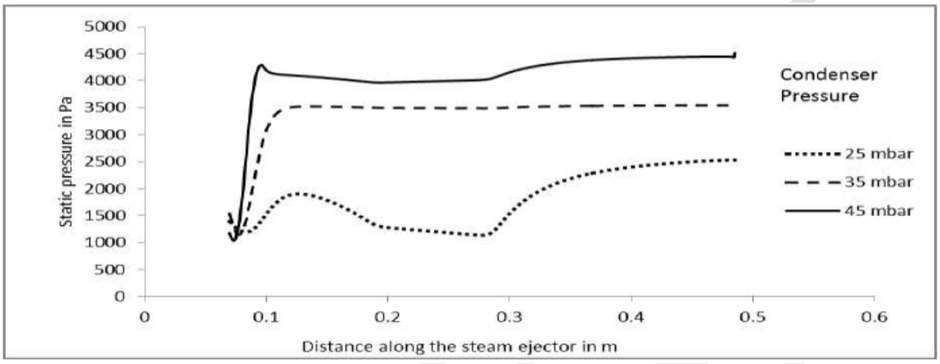


Fig.7: Static pressure profile along ejector and effect of condenser pressure

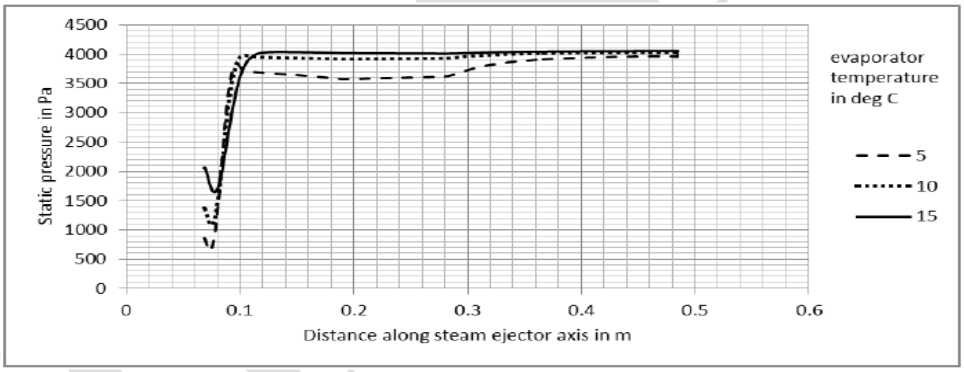


Fig.8: Static pressure profile along ejector and effect of evaporator temperature

The primary nozzle dimension was varied and the steam ejector performance was studied at boiler temperature of 130^{0}C, evaporator temperature of 5^{0}C and at a condenser pressure of 35 mbar. Fig.9 shows the variation of static pressure along the steam ejector. The entrainment ratio was calculated and it was found that the entrainment ratio increases as the throat diameter was reduced. When a smaller primary nozzle was used, smaller amount of primary mass expanded through the primary nozzle. The enlargement of the entrained duct can be investigated from the moving downstream of the effective position.

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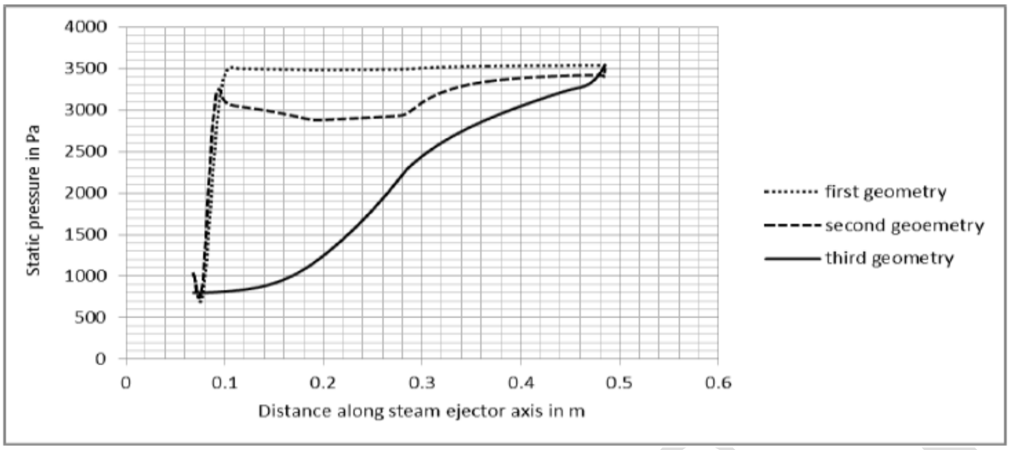

Fig.9: Static pressure profile along ejector, effect of primary nozzle throat diameter.

The primary mass flow rate can be calculated by subtracting the outer and inner stream function values; similar procedure is used to calculate the secondary mass flow rate. Primary mass flow rate (m_p) = [0.000552 – 1.5 x 10^{-5}] x 2 = 1.074 x 10^4 . Secondary mass flow rate (m_s) = [0.001254 – 0.000582] x 2 = 1.344 x 10^{-3} . Entrainment ratio (E.R)= $mp_/ m_s$ = 1.25

V. CONCLUSION

Based on the computational investigation to analyze the performance of a steam ejector working in conjunction with a refrigeration cycle, The CFD code employing Spallart-Allmaras turbulence model is capable of predicting the performance characteristic of the steam ejector. The Entrainment ratio (ER) is found to increase with the decrease of boiler saturation temperature for the same condition of superheat, evaporator temperature and condenser pressure. The entrainment ratio is also found to increase with increase of evaporator temperature. The entrainment ratio does not vary much with the condenser pressure until the critical condenser pressure. The shocking position is found to move backward as the condenser pressure is increased. The Entrainment ratio is also found to increase with the decrease of throat diameter. But mass of primary fluid is also reduced which results in the moving downstream of the shocking position.

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BIOGRAPHY

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Dr. P. Ravinder Reddy was born on August 12th 1965, graduated in B.Tech Mechanical Engineering from Kakatiya University (1987) Warangal, M.E Engineering Design from PSG college of Technology, Coimbatore (1991) and Ph.D from Osmania University in 2001. He has 26 years of Teaching, Industrial and Research experience. He published over 205 technical and research papers in various international and national journals and conferences. He has guided 11 Ph.D scholars so far. As a facilitator for the learning process organized 27 STTPs/Workshops /FDPs /SDPs, 2 international conferences beneficial to Faculty, Researchers and Industry and delivered 105 keynote and invited talks. Was a chief and principal investigator for 17 research and 27 industrial consultancy projects sponsored by AICTE, UGC, NSTL, DRDL, BHEL, RR Industries, ICOMM Tele services and ACD communications. He is a recipient of **Raja Rambapu Patil National award** for promising Engineering Teacher by ISTE for the year 2000 in recognition of his outstanding contribution in the area of Engineering and Technology, **Excellence "A" Grade** awarded by AICTE monitoring committee (2003) for the MODROB project sponsored by AICTE, "**Engineer of the year Award-2004**" for his outstanding contribution in Academics and research by the Govt. of Andhra Pradesh and Institution of Engineers (India), AP State Centre on 15th September 2004 on the occasion of 37th Engineer's Day, **Best Technical Paper Award** in the year Dec. 2008 in Industrial Application titled "Online quality monitoring welding &weld upset in resistance projection welding process", in Journal of Non-Destructive Testing &Evaluation, the official journal of ISNT during the year 2007 by National Governing Council of Indian Society for Non Destructive Testing