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AN EXPERIMENTAL STUDY OF THE EFFECT OF TWO PHASE (AIR-WATER) FLOW CHARACTERISTICS ON MOMENTUM FLUX DUE TO FLOW TURNING ELEMENTS AT ATMOSPHERIC CONDITIONS

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Abstract-In the case of two-phase flow, the momentum fluxes due to flow turning elements like bends, elbows etc.at the end of pipe are the major cause of flow-induced vibrations (FIV) .In this work, an experimental set up has been developed to study the effect of two phase flow (air-water) characteristics on momentum flux for the different support condition of test section i.e. cantilever end condition and both end fixed condition. To carry out the experiments, the test section is made of steel material of 0.0239 m in diameter and 1.2 m in length. The experiments are carried out for different flow regimes and void fraction. The mass flow rate of air and water flowing through test section are varied simultaneously to obtain the different types of flow characteristics or flow regimes. At the same time, the momentum flux induced due to two phase flow (air-water) are measured using momentum flux apparatus(load cell) fixed close to at the exit of test section. The results of experimental analysis are compared with those obtained with CFD (Fluent 15.0) analysis software. And it is seen that there is good agreement between the results of experimental and CFD analysis and found to be satisfactory with 4 to 20 % error for different support end condition i.e. cantilever end and both end fixed for all types of flow characteristics.
Keywords— Two Phase Flow, Flow Regimes, Void Fraction, Momentum Flux, Flow induced vibration (FIV), Computational Fluid Dynamic (CFD)

NOMENCLATURE:-

A	Cross sectional area of test section, m^2
D	Internal diameter of test section, m
L	Length of test section, m
Q_W	Volume Flow Rate of Water, m^3/s
Q_A	Volume Flow Rate of Air, m^3/s
m_w	Mass Flow Rate of Water, kg/s
m_A	Mass Flow Rate of Air ,kg/s
V_A	Superficial Velocity of Air , = Q_A /A , m/s
V_W	Superficial Velocity of Water, = Q_W /A, m/s
α	Void Fraction

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h_A	Manometer Reading of Water For Air Flow Measurement, m
h_G	Manometer Reading of Mercury For Water Flow Measurement, m
μ_A	Dynamic Viscosity of Air, Ns/m^2
μ_W	Dynamic Viscosity of Water, Ns/m^2
ρ_A	Density of Air, kg/m^3
ρ_W	Density of Mercury, kg/m^3
V_m	Mixture Velocity = ($V_A + V_W$), m/s
N	Momentum Flux

I INTRODUCTION

The fluctuation of momentum flux due to flow turning element like bends, elbows etc. in two phase flow is possible source of pipe vibration in piping systems in the chemical, petroleum, nuclear and power industries. Depending upon flow regimes, there is presence of gas bubbles, liquid slugs or waves in two phase flow which leads to the generation of sever pulsation in pressure, void fraction and momentum flux. The flow induced vibrations caused due to the fluctuation of momentum flux leads to undesirable effects of engineering systems such as fatigue failures of components, the periodic relative motion between components or systems leading to wear, disturbing the normal function of the system. Also the huge economic loss to enterprises is incurred due to significant increase in accidents caused by flow-induced vibration. Hence, it is necessary to study damage caused by flow-induced vibration for ensuring longer life and operate piping system with best efficiency.
Oshinowo [1] carried out experiments in a 0.025 m diameter pipe in vertical upward and downward co-current air-water flow. He observed different flow patterns such as coring bubbly, bubbly- slug, falling film, froth and annular (annular- mist flow) patterns. Yamazaki and Yamaguchi [2] considered two phase phenomenon in a 0.025 m diameter pipe with air-water as working fluid. The flow patterns are observed by visual observation and photographic techniques. Paras [3] studied experimentally two phase flow in a 0.0195 m diameter pipe oriented downwards using air-water as working fluid and observed slug flow with successive Taylor bubbles separated by water slugs. In case of bubbly flow, there is random distribution of bubbles axially but they have a definite tendency to move to the center of pipe. Lamari [4] worked out in his thesis about an experimental study of two-phase (air-water) flow regimes at near atmospheric conditions in a horizontal tube. The different flow regimes such as stratified wavy, plug, slug, and annular flow regimes are observed. The physical mechanism which governs the change between these regimes are also discussed. Subramanian [5] has presented a paper on elementary aspects of two-phase flow in pipes. In this paper, the different types of flow regimes i.e. bubble, churn, stratified, slug and annular flow obtained by varying the velocity of gas and liquid are discussed. Griffith [6] has presented desertion work on the measurement of the steady and unsteady components of the momentum flux in two phase flow at the exit of a vertical pipe. The measured momentum flux data has been machine processed by standard random vibration techniques to obtain the power spectral density curves. The effects of the average flow velocity, volumetric quality, system pressure, flow channel size and geometry on the unsteady momentum fluxes have been observed.

II METHODOLOGY

Based on the above literature review on flow induced vibration (FIV) due to two phase flow, momentum flux and flow patterns studied by many researchers, it is clear that there are no quantitative measures to decide upon the existence of distinguished flow patterns and momentum flux. Hence an experimental set up has been fabricated to obtain different flow regimes and study the effect of these different flow regimes on momentum flux.

II A EXPERIMENTAL SET UP

Figure 1 shows the schematic diagram of the experimental set-up to obtain different flow régimes. It consists of a centrifugal pump (1.5hp, 1440 rpm) which is used to pump the water through a test section from a water reservoir .The flow rate of water from the pump is regulated using flow control valve which is measured by calibrated venturimeter with the help of manometer. To have two phase flow (Air-Water), an air compressor (0-7 kg/cm^2, 2 hp, 2850 rpm) which is used to provide compressed air at regulated outlet pressure using flow control valve. The flow rate of air is measured by calibrated orificemeter with the help of manometer. Both air and water is passed through a mixing section to form different flow patterns. The viewing section is provided with glass view port of 0.5 m in length and 0.0256 m in diameter for observing different flow characteristics obtained. The test section is made of steel material of 0.0239 m in diameter and 1.2m length fixed at one end for cantilever condition and both end fixed condition as shown in Figure 2 (a) and Figure 2 (b).

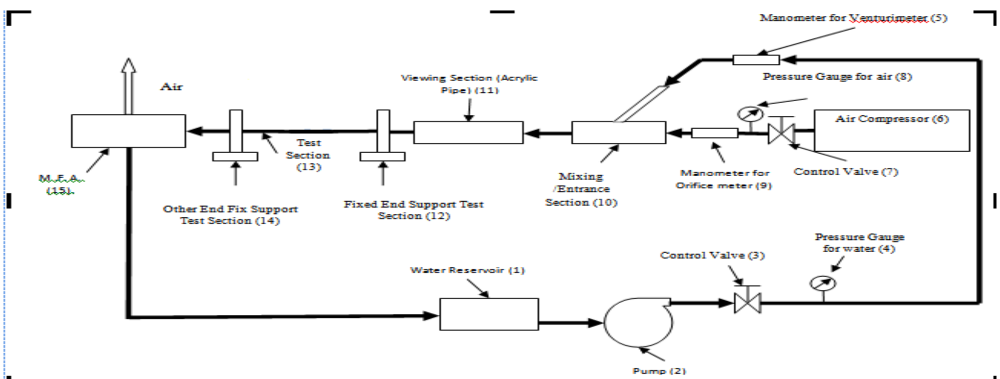


Figure 1 Experimental Set Up For Two Phase Flow Characteristics and Measurement of Momentum flux.

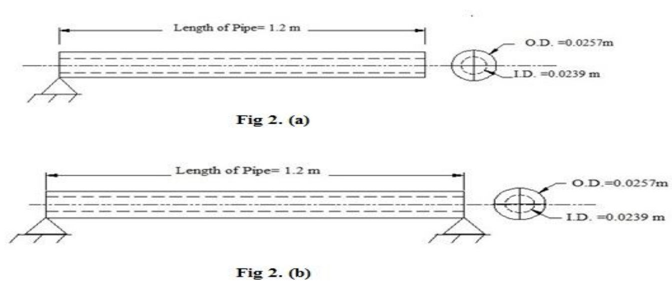


Figure 2 Test Section (a) Cantilever End, (b) Both End Fixed Condition

The momentum flux apparatus (load cell-CZL601) is fixed close to the exit of free end of cantilever test section as shown in Figure 3 and the output of momentum flux apparatus connected to computer to measure momentum flux induced in the pipe. Again the momentum flux apparatus (load cell) is fixed close to the other end of test section both end fixed condition and the output of momentum flux apparatus is connected to computer to measure momentum flux induced in the pipe due to two phase flow.

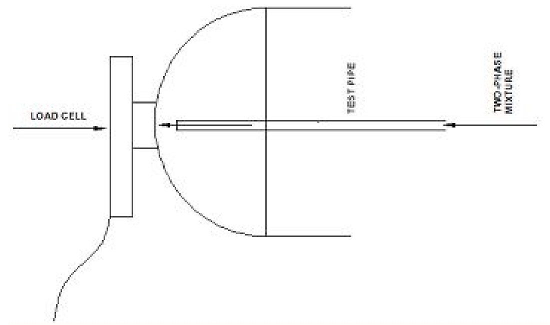


Figure 3 Momentum Flux Apparatus

From the velocity of water and air, corresponding volume flow rate of water and air, mass flow rate of water and air and void fraction is calculated from the formulae. Similar procedure is followed for other flow patterns such as bubbly, elongated bubbly, stratified smooth and stratified wavy are obtained by varying simultaneously velocity of water and velocity of air and corresponding the momentum flux induced in the test section for cantilever end condition and for both end fixed condition were measured as shown in Table 1.The corresponding flow patterns are observed and recorded using high speed high resolution camera.

II B MEASUREMENTS OF INPUT PARAMETERS

1 Volume Flow Rate of air, Q_A ,m^3/s

An orifice meter is used to measure the volume flow rate of air. This device determines the superficial air velocity by measuring the manometer reading of water. Orifice meter was placed with sufficient upstream and downstream straight-run piping to ensure that the airflow was fully developed at the location where it was being measured.

$Q_A = C_{do} \times a_A \times \sqrt{2gh_A}$, m^3/s, [10]

2 Volume Flow Rate of Water, Q_w , m^3/s

A venturimeter is used to measure the volume flow rate of water. It is placed in a 0.0127 m steel tube with sufficient upstream and downstream straight-run piping to ensure that the water flow was fully developed. This device determines the superficial velocity of water by measuring the manometer reading of mercury.

$Q_W = C_{dv} \times a_W \times \sqrt{2gh_W}$, m^3/s , [10]

II C MEASUREMENTS OF OUTPUT PARAMETERS

The output two-phase flow parameters to be measured are the mixture velocity of water and air and the void fraction,

C.1 Mixture Velocity, $Vm = (V_A + V_W)$, m/s

Mixture velocity is sum of the superficial velocity of water and the superficial velocity of water.

C .2 Momentum Flux

The steady component of the momentum flux in a two phase flow has been measured at the exit of a horizontal test section with the help of momentum flux apparatus as shown in Figure 3. It consists of hemispherical pan made of sheet metal and load cell (CZL601).By means of a turning tee ,the momentum fluxes of the air-water flow at the exit plane of the horizontal test pipe is converted into a force which acts upon the beam (load cell) built inside the momentum flux apparatus. The displacement of the beam is then picked up by a transducer (calibrated load cell). The load cell gives its output in terms of force N (momentum flux) due to flow turning element like bend, elbows etc. Each flow patterns such as annular, bubbly, elongated bubbly, stratified smooth and stratified wavy are obtained by varying simultaneously velocity of water and velocity of air and corresponding momentum flux induced in test section are measured from load cell (momentum flux apparatus) for different flow patterns and different support condition i.e. for cantilever end and both end fixed condition experimentally. For CFD analysis, Ansys Fluent 15.0 is used to measure momentum flux for each flow characteristics. From the reading experimental analysis and CFD analysis, the graphs are plotted mixture velocity against momentum flux as shown in Figure 11.

III CFD ANALYSIS

For the validation of experimental work, an aid of commercial CFD software ANSYS Fluent 15.0, ANSYS Transient Structural 15.0 is taken to numerically model the two phase flow through steel pipe. The analysis is carried out by considering the phenomenon as Fluid – Structure Interaction. The working fluid considered in the present case is two phase (air-water) at atmospheric condition.

Governing Equation

Following governing equations expressing conservation of mass, momentum are used for the solving problems are described consequently;

i) Continuity Equation

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla.\left(\alpha_q\rho_q\overrightarrow{v_q}\right)=s_{\alpha_q}+\sum_{p=1}^{n}\left(m_{pq}\dot{-}\dot{m}_{pq}\right)+s_{\alpha_q}\right]$$

[12]

ii) Momentum Equation

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla.(\rho\,\vec{v}\vec{v})=-\nabla p+\nabla.[\mu\,(\nabla\,\vec{v}+\nabla\,\vec{v}^{T})]+\rho\,\vec{g}+\,\vec{F}$$ [12]

A. Modeling of the Tube

3-D tube is modeled in ANSYS 15.0 meshing and exported to FLUENT. Analysis is carried out for grid independent study and the optimum mesh size is selected having nodes 30804 and elements 20779. The meshed model of pipe is shown in Figures 4, 5 and 6.

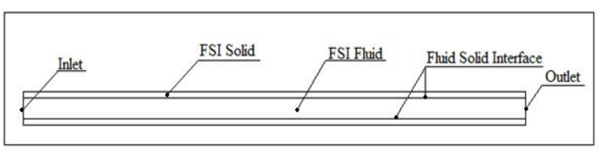


Figure 4, 2 D sketch of Computational Domain

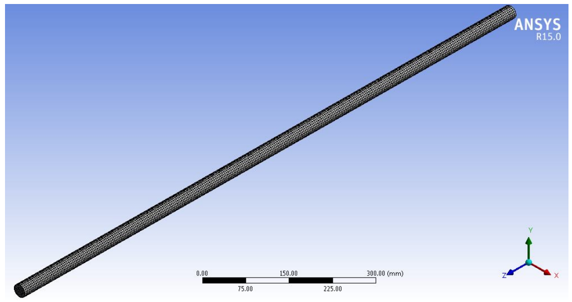


Figure 5 Isometric view of meshed 3D pipe

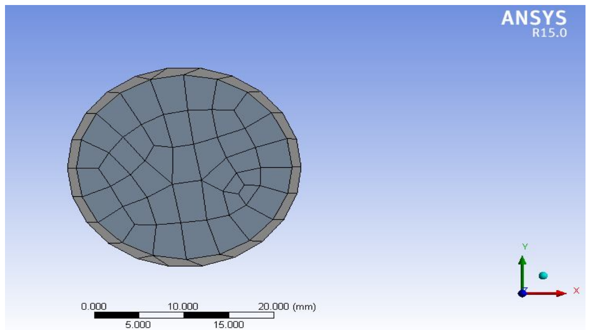


Figure 6 Side view of meshed 3D pipe

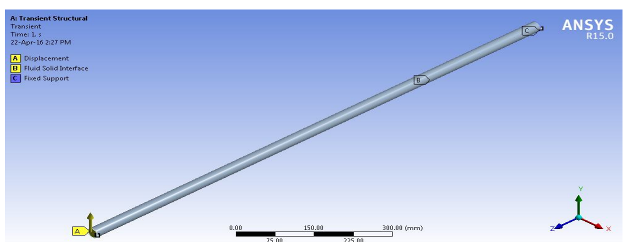


Fig. 7 Setup conditions for Transient Structural analysis (Cantilever)

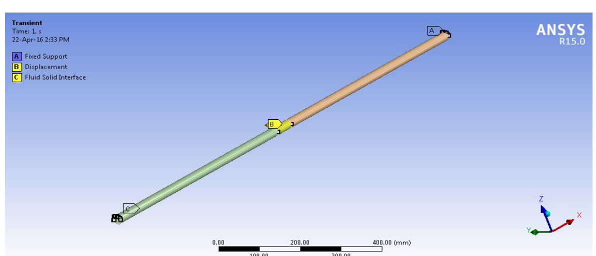


Figure 8 Setup conditions for Transient Structural analysis (Both End Fixed)

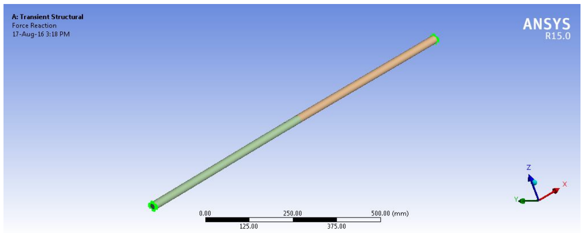


Figure 9 Momentum flux at both end fixed

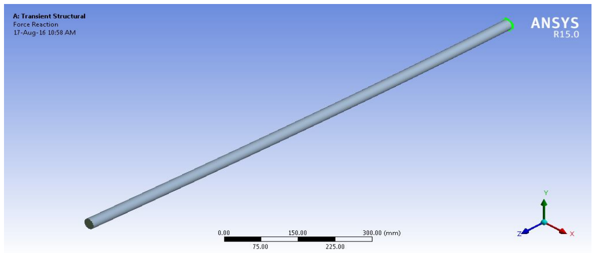


Figure 10 Momentum flux at one end fixed (Cantilever End)

B. Selection of Solver

The solver conditions are set for transient flow. The pressure-based solver with Mixture model and Transient Structural is used for Fluid Flow and Structure interaction respectively. Transient 3D planar simulation is activated along with absolute velocity formulation.

C. Selection of Viscous Model

Since for the entire range of flow rates, SST k-w, model is considered.

D. Material Properties

Using these solver conditions set, for each quality (void fraction), average properties are calculated for air and water.

E. Setting of Operating Conditions

The operating pressure is set at atmospheric condition considered for each flow patterns.

F. Applying the Boundary Conditions

At inlet (z=0): $u = v = 0, P = P_{atm}$

At outlet (free surface, $z = z_{max}$): $u = v=0, P = P_{atm}$

At wall (y=0): w=0

Wall: No slip condition is given at the wall.

G. Solution Controls

Coupled solver is selected for Pressure – Velocity, Coupling. This solver uses explicit scheme. For the discretization of momentum and pressure, QUICK scheme and Body force weighted schemes are used respectively.

H. Convergence

A convergence criterion of 0.001 is considered.

I. Post Processing

Thus for every void fraction and flow patterns at each flow rate, the model is simulated to get the mixture velocity, void fraction and acceleration data.

IV. OBSERVATIONS

The comparison between the results of experimental analysis of momentum flux and CFD software results is given in Table 1:-

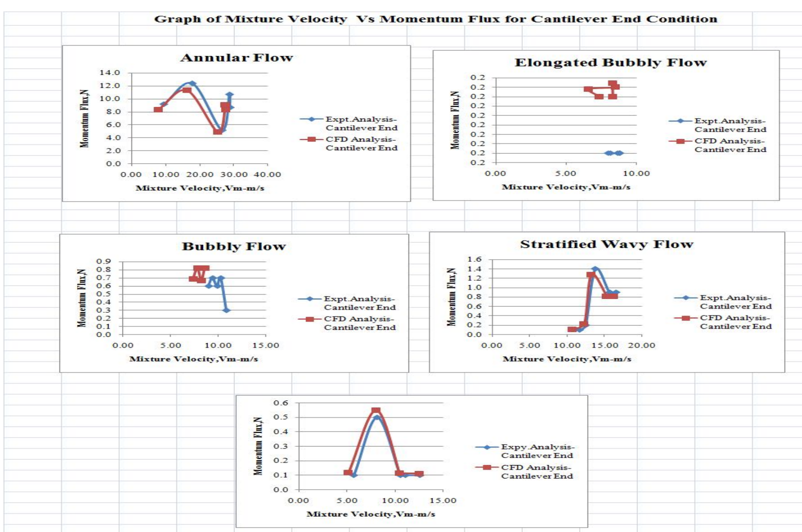
*Comparision Between The Reults of Momentum Flux of Experimental Analysis and CFD Software Analysis of Two Phase Flow													
	Type of flow- by visual inspection						Cantilever End Condition			Both End Fixed			
Sr. No		Velocity of water (m/s)	Velocity of Air (m/s)	Mixture Velocity,m /s	Mixture Velocity,m /s (CFD Software)	% deviation Mixture Velcity	Momentum Flux (N) Reading from force transducer-load cell, N	Momentum Flux (N) CFD Software	% deviation Momentum Flux	Momentum Flux (N) Reading from force transducer-load cell, N	Momentum Flux (N) CFD Software	% deviation Momentum Flux
1	ANNUAL AR FLOW	1.1218	8.3384	9.46	7.75	18.08	9.2	8.290	9.89	11.3	12.52	10.80
2		1.1168	16.6767	17.79	16.30	8.39	12.4	11.310	8.79	12.4	14.81	19.44
3		1.1168	25.4286	26.55	25.30	4.69	5.2	4.900	5.77	10.4	10.09	2.98
4		1.1119	27.6552	28.77	27.50	4.40	10.7	9.050	15.42	7.8	8.01	2.69
5		1.1168	27.7807	28.90	27.63	4.39	8.7	8.290	4.71	13.9	14.02	8.66
6	ELONGATED BUBBLE FLOW	0.4815	7.4581	7.94	7.30	8.05	0.2	0.230	15.00	0.1	0.11	10.00
7		1.1267	6.9764	8.10	6.57	18.92	0.2	0.234	17.00	0.1	0.113	13.00
8		0.2780	8.3384	8.62	8.44	2.05	0.2	0.235	17.50	0.2	0.221	10.50
9		0.4203	8.3384	8.76	8.26	5.69	0.2	0.237	18.50	0.2	0.223	11.50
10		0.4203	8.3384	8.76	8.26	5.69	0.2	0.230	15.00	0.2	0.224	12.00
11	BUBBLE FLOW	1.0559	7.9105	8.97	7.35	18.03	0.6	0.690	15.00	0.5	0.561	12.20
12		1.0454	8.3384	9.38	7.81	16.77	0.7	0.820	17.14	0.5	0.558	11.60
13		1.1119	8.7454	9.86	8.19	16.91	0.6	0.670	11.67	0.5	0.557	11.40
14		1.0969	9.1342	10.23	8.55	16.43	0.7	0.820	17.14	0.5	0.559	11.80
15		0.9397	9.8661	10.81	9.40	13.01	0.3	0.330	10.00	0.5	0.561	12.20
16	STRATIFIED WAVY FLOW	0.7503	10.8719	11.62	10.66	8.28	0.1	0.118	18.00	1.5	1.6	6.67
17		0.3322	12.0834	12.42	12.22	1.58	0.2	0.231	15.50	4.4	4.5	2.27
18		0.5253	13.1841	13.71	13.18	3.86	1.4	1.280	8.57	1.9	2	5.26
19		0.4699	15.1474	15.62	15.29	2.10	0.9	0.820	8.89	1.4	1.5	7.14
20		0.4203	16.0392	16.46	16.18	1.70	0.9	0.820	8.89	1.2	1.35	12.50
21	STRATIFIED SMOOTH FLOW	0.4069	5.2736	5.68	5.12	9.87	0.1	0.119	19.00	1.5	1.6	6.67
22		0.2101	7.9105	8.12	8.01	1.36	0.5	0.550	10.00	0.6	0.67	11.67
23		0.3322	10.2124	10.54	10.44	0.99	0.1	0.116	16.00	0.3	0.34	13.33
24		0.5147	10.5473	11.06	10.44	5.62	0.1	0.115	15.00	0.8	0.912	14.00
25		0.2101	12.3678	12.58	12.46	0.94	0.1	0.113	13.00	0.2	0.231	15.50
		* The frequnce of redings are taken at the interval of 10 sec.										

Table 1 Comparison between the results of experimental analysis of momentum flux and CFD software results

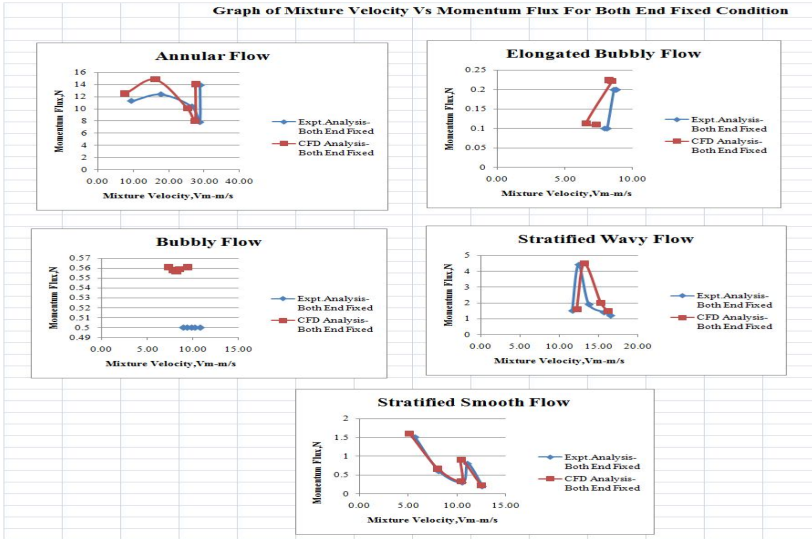
V.GRAPHS

The graphs of the comparison between the results of experimental and CFD analysis (momentum flux) is as shown below. Figure 11 (a) and (b) Mixture Velocity Vs Momentum Flux for Cantilever End and Both End Fixed

V.1 for Cantilever End Condition as shown in figure11 (a)



V.2 for Both End Fixed Condition as shown in figure11 (b)



V CONCLUSION

From the results presented on momentum flux, there is good agreement between the experiment results with those obtained and CFD analysis and they are found to be satisfactory with 4 to 20% of error for different support condition i.e. the cantilever end and the both end fixed condition. In the bubbly flow regimes, although the density and velocity are not uniform along flow section, the total momentum flux remains almost a constant with respect to time. For the elongated bubbly (slug) and annular flow regimes; the flow density across a section varies rapidly with time. The velocity of the increased liquid portion, i.e., waves in annular flow or core of liquid slug in slug flow is always higher than the average velocity of the liquid phase. For stratified wavy flow, flow density of water across the test section is decreases and flow density of air increases rapidly thus causing momentum flux increases for cantilever end and for both end fixed condition both experimentally as well as CFD analysis .

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