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Modeling of Mixing Diesel-CNG in a Horizontal Pipe under the Influence of a Magnetic Field

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ABSTRACT—*The pre-mixing of Diesel and CNG has been suggested to improve the quality of the injected fuel in the cylinder more than if a mixture of CNG-air is injected in the cylinder, directly. The nature of the pre-mixed Diesel and CNG is gas-liquid bubbly flow. The objective of the present paper is to study the behavior of gas bubbles in the liquid fuels and the ways to control the bubbles sizes prior to injection by an external magnetic field. Modeling of Diesel-CNG bubbly flow with effecting magnetic field is presented in this paper. The incompressible Navier-Stokes equations have been used to solve the Diesel-CNG two phase flows in a horizontal pipeline. The simulation was carried out using ANSYS fluent software and the flow field discretization was achieved by the Volume-Of-Fluid method (VOF) technique. The interface between the gaseous and liquid phases was described by a phase field function V_F, when the phase interface crosses a mesh element- $0 < V_F < 1$. The results showed that CNG bubbles tend to migrate toward the upper wall under buoyancy effect and these bubbles grow to a larger volume and expand vertically in the diesel flow before it breaks away with effecting magnetic field 0.4 to 0.8 Tesla, and the gas volume fraction values increased by increasing the magnetic intensity. The laminar behavior of the flow changed in the upper zone of the pipe to increasing gas volume fraction, while the axial diesel velocity decreased and the profiles tended to flatten with increasing the magnetic field strength. The numerical procedure was validated by comparing the computational results with experimental data reported in the literature and a good agreement was achieved.*

Keywords— Two-phase flow, Bubbly flow, Magnetic field, Volume-of-fluid (VOF)

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1. INTRODUCTION

The analysis of liquid-gas flow dynamics under electric and magnetic fields has become an important effect in the design and control of many electric-apparatus systems, such as magneto hydrodynamic problems (MHD), gas and oil facilities, processing nuclear reactors, and MHD power stations [1]. In diesel engines, the new idea of pre-mixing Diesel and CNG was suggested to increase the air quantity inside the cylinder more than if a mixture of CNG-air is injected in the engine which may result is a rich mixture [2]. This mixture requires a study of the behavior of gas bubbles in the liquid fuels and ways to control on their size before arriving in the injection system through the influence of external forces, such as a magnetic field, where the horizontal bubbly flow pattern is characterized by the presence of bubbles dispersed in a continuous liquid phase, with their maximum size being much smaller than the diameter of the containing pipe. This particular flow orientation has received less attention when compared to vertical bubbly flow. An additional difficulty arises in this case, as the migration of dispersed bubbles towards the top of the pipe, due to buoyancy, causes a highly non-symmetric volume fraction distribution in the pipe cross-section Ekambara et al. [3]. Sussman and Smereka [4] discussed that an example of complex flow simulation is the flow of two fluids with high density and viscosity ratios, such as bubbly and droplets flows. They stated that the main concern is the gas bubble behavior and it's deforming in a viscous liquid. The mechanism of movement of the bubbles and the action of coalescence and bubble break-up is due to high density and viscosity ratios as well as topology changes. Hence, the inspection of the shape of the bubble domain in sporadic flows is very important to enhance the expectancy of the flow structure, flow pattern transition, as well as definition of a wide range of fluid properties. On other hand, Bhaga and Weber [5] have experimentally determined the shape and velocities of bubbles in viscous liquids; while, Ryskin and Leal [6] developed a numerical method to compute the steady motion of a bubble in the liquid. Brunner et al. [7-8] suggested that the flow pattern may be controlled by electro-hydrodynamic forces, and several flow pattern transition mechanisms were presented.

Most popular numerical methods for interface tracking are Volume-of-Fluid (VOF) technique implemented in ANSYS Fluent or Level-Set (L-S) method in COMSOL Multiphysic [9]. It can be said that the study of the bubbly flow in a flow field under magnetic impose is new approach. So far, Ishimoto et al. [10] have studied experimentally the effect of non-uniform magnetic field on a bubbly flow; and compared his results with the numerical and experimental results reported by Hnat and Buckmaster [11], where excellent agreement have been achieved.

A literature review shows that various researchers have studied the effects of non-uniform magnetic fields on two-phase flows or uniform magnetic fields on electric conductive vertical two-phase flows. But the effects of change in intensity of a uniform magnetic field on bubbly flow in horizontal pipes, and its impact on fuel mixtures has not been studied in details.

Hence the main objective of this study is to investigate the effect of change in intensity of a uniform magnetic field on bubbly flow (Diesel-CNG) in a horizontal pipe. The bubbly flow behavior of CNG in Diesel is to cover a wide range of two phase flow properties (velocities, volume fraction, and behavior of CNG bubbles). For that, bubbles of CNG in Diesel flow have been simulated using ANSYS fluent software. Volume-Of-Fluid method has been adopted for the simulation and analysis. The results of the CNG bubble behavior, in terms of volume fraction and distribution, as well as the Diesel velocity effect, have been presented in this paper for various magnetic field intensities on Diesel-CNG flow.

2. COMPUTATIONAL MODELLING

The computational fluid dynamics (CFD) is based on the numerical solutions of the fundamental governing equations of fluid dynamics namely the continuity, momentum, energy, species concentrations, and turbulence equations, of two phase flow [12]. The FLUENT software package was used to accomplish this job.

2.1 Governing equations

Bubble flow dynamics in electrically conductive liquid subjected to an external DC electromagnetic field can be characterized by the following set of equations [13]:

$$\nabla^2 \vec{B}/(\mu_o \sigma_l) + (\vec{B}.\nabla)\vec{U} - (\vec{U}.\nabla)\vec{B} = 0 \tag{1}$$

$$\vec{J} = \sigma_l(-\nabla\varphi + [\vec{U} \times \vec{B}]) \tag{2}$$

Where $\vec{B}$ is magnetic field induction, μ_o - magnetic constant, σ_l - electrical conductivity of liquid, $\vec{U}$ - velocity, the pair of equations describing the electromagnetic nature of the process are Amperes circuital law (1) (where displacement currents are neglected), and Ohm's law (2) [13].

$$\nabla.\vec{U} = 0 \tag{3}$$

$$\frac{\partial \vec{U}}{\partial t} + (\vec{U}.\nabla)\vec{U} = -\frac{1}{\rho_l}\nabla p + \upsilon_l \nabla^2 \vec{U} + \vec{K} \tag{4}$$

Where p is Pressure, υ_l is the kinematic viscosity of the liquid,

$\vec{K}$ is the sum of volume forces, which are:

$\vec{K}_{fric} = N(\Delta\vec{U}_{\mathrm{lg}})/\rho_l$ is the friction force,

$\vec{K}_{Lor} = (\vec{J} \times \vec{B})/\rho_l$ is the Lorentz force,

$\vec{J}$ is the current density, and

$\vec{K}_g$ is the drag force.

Equations 3 is denoting the hydrodynamic processes of conductive viscous liquid, and Equation 4 is denoting the momentum balance [13].

2.2 Volume of fluid method (VOF)

Phase distribution can be characterized by a phase field function V_F (ri, t) ($^i th$ mesh element is given a scalar value V_F). If the mesh element does not contain melt then $V_F = 0$, otherwise - $V_F = 1$ and the mesh element is completely filled with melt. And when the phase interface crosses the mesh element - $0 < V_F < 1$. In general, the interface dynamics is characterized by the following transport equation:

$$\frac{\partial V_F}{\partial t} + \vec{U}.\nabla(V_F) = 0 \tag{5}$$

2.3 Methodology

The methodology adopted for the present work is as follows. Diesel flows through a horizontal pipeline (20 mm diameter and 100 mm long) and CNG gas is injected axially (2 mm nozzle diameter). An external magnetic field affects the flow perpendicular to the two phase flow direction to study the CNG bubbles' behavior. Figure 1 show the suggested scheme, which includes the following steps:

- Solid modelling of a horizontal pipeline with axial gas injector.
- Mesh generation.
- Solution of the governing equations with appropriate boundary conditions.
- Comparison of the simulated results with the available experimental results reported in the literature.

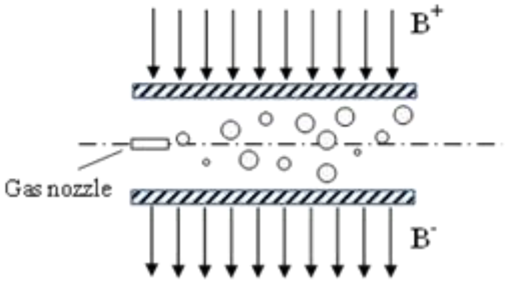


Figure 1: The suggested scheme of CNG bubbles in the Diesel liquid flow.

The study is expected to explore the potential of using ANSYS Fluent software tools for analysis of two phase flow characteristics. The package includes user interfaces to input problem parameters and to examine the results. The three-dimensional model of the mixture is developed by using the pre-processor CFD software. The number of cells used in this model was 297,423. Mesh refinement investigation was carried out to optimize the number of cells used. It was found that increasing the number of cells to 317,688 and 347,730 had no effect on the results accuracy. Hence, 297,423 were selected to be the optimum number of cells that can be used in the simulation. Figure 2 shows (a) the solid modelling and (b) the mesh for the case under study.

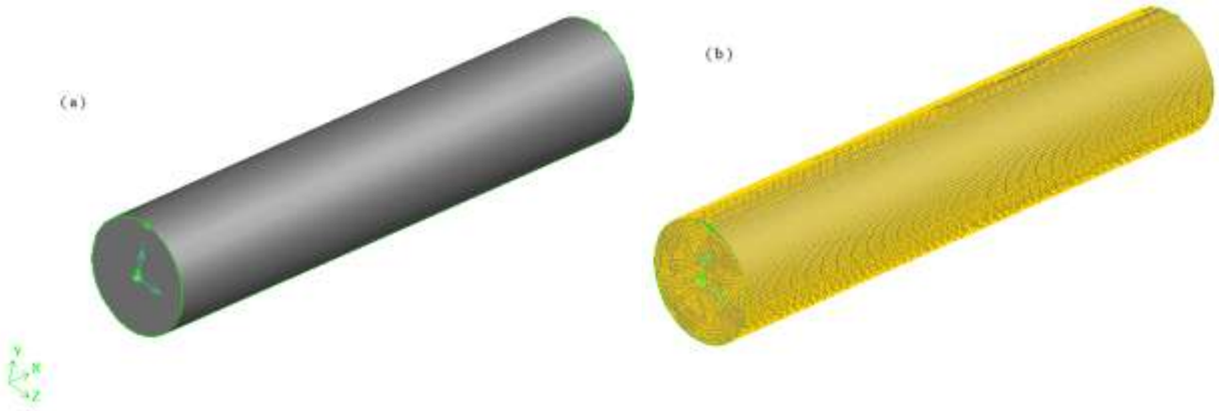


Figure 2: (a) The solid modeling, and (b) the normal type mesh for the case under study

2.4 Boundary conditions

Consider an unsteady, (i.e., the bubble velocity and distribution are function of time and location along the pipe and radius), laminar, hydro-magnetic, fully developed, CNG gas injection in Diesel flow in a horizontal pipeline. A uniform transverse magnetic field is applied normal to the flow direction (see Figure 1). The Diesel phase is assumed to be electrically conducting depending on the sulphur content of the fuel [14]. No electric field is assumed to exist and the hall effect of MHDs is negligible. The governing equations for this study are based on the conservation laws of mass and momentum of both phases. Attached boundaries are specified on the coincident cell face near the cells around CNG bubbles. No slip wall boundary condition in conjunction with logarithmic law of wall is used. Table 1 gives the properties of Diesel fuel and CNG [15].

Table 1: P Properties of DIESEL fuel and CNG [15]

Parameter	Diesel	CNG
Density (kg/m^3) (23 ^{o}C)	830	0.73
Viscosity (N.s/m^2) (23 ^{o}C)	0.0024	$7.8*10^{-6}$
Carbon (%, w/w)	86.83	73.3
Hydrogen (%, w/w)	12.72	23.9
Oxygen (%, w/w)	1.19	0.4
Sulphur (%, w/w)	0.25	ppm < 5
Electric Conductivity (1/Ω.m)	25	-
Relative permittivity	2.2	-

The inlet mean velocity of diesel was 0.175 m/s and CNG was injected into the flow, the CNG velocity was equal to zero when (t = 0) (in injection time). Different magnetic field intensity changed (0, 0.4, and 0.8 Tesla) were used.

3. RESULTS AND DISCUSSION

3.1 Sensitivity analysis on CNG volume fraction profile

In order to understand the effect of different forces, the numerical simulations were carried out for three different cases. In the first case, the 3D simulations are carried out taking friction force and drag force into account while the magnetic force (Lorentz force) was neglected (B= 0), the predicted volume fraction profile showed a peak at the top of the pipe, where CNG bubbles tend to migrate toward the upper wall. Figure 3 shows contours of CNG volume fraction in the diesel flow at (B = 0) and during different times: (a) 0.1 sec, (b) 0.3 sec, (c) 0.5 sec, (d) 1.0 sec, (e) 1.5 sec. guidelines).

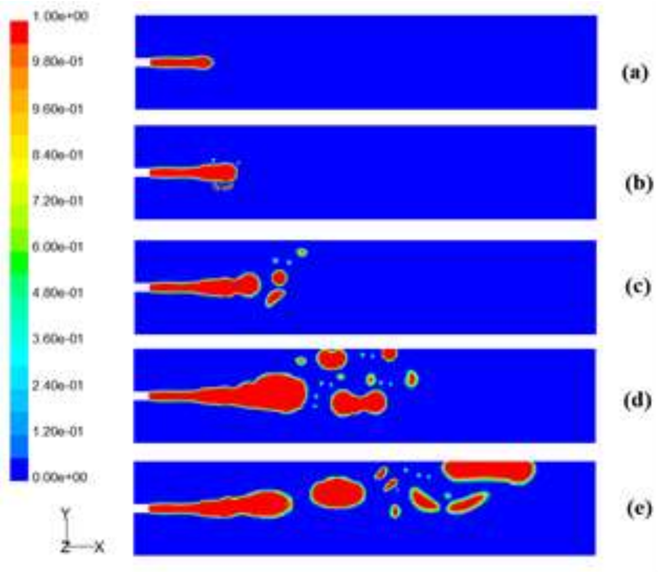


Figure 3: Contours of CNG volume fraction to Diesel-CNG bubbly flow at (B = 0) and during different time: (a) 0.1 sec, (b) 0.3 sec, (c) 0.5 sec, (d) 1.0 sec, (e) 1.5 sec

In the second case, the simulations were carried out including a magnetic force with (B = 0.4 Tesla). The result showed a significant change and the behavior was basically the same with bubbles tending to migrate toward the upper wall but CNG bubbles grew to a bigger volume and expanded vertically in the diesel flow before it broke away in 0.4 Tesla. Figure 4 shows contours of CNG volume fraction in diesel flow at (B = 0.4 Tesla) and during different times: (a) 0.1 sec, (b) 0.3 sec, (c) 0.5 sec, (d) 1.0 sec, (e) 1.5 sec. In the third case, when the magnetic force was increased (B = 0.8 Tesla), the CNG volume fraction profile showed acceleration in this mechanism with the same behavior for the elongation of the bubble in a vertical direction of the diesel flow. These results show good agreement for the effect of magnetic force with the experimental and numerical data of Ishimoto et al. [10], Hnat and Buckmaster [11] in vertical bubbly flow and Fern´andez [16] on hydrogen bubble.

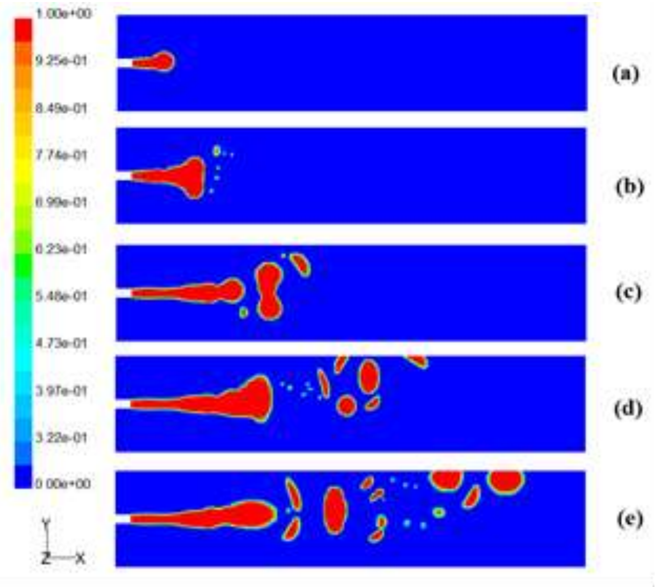
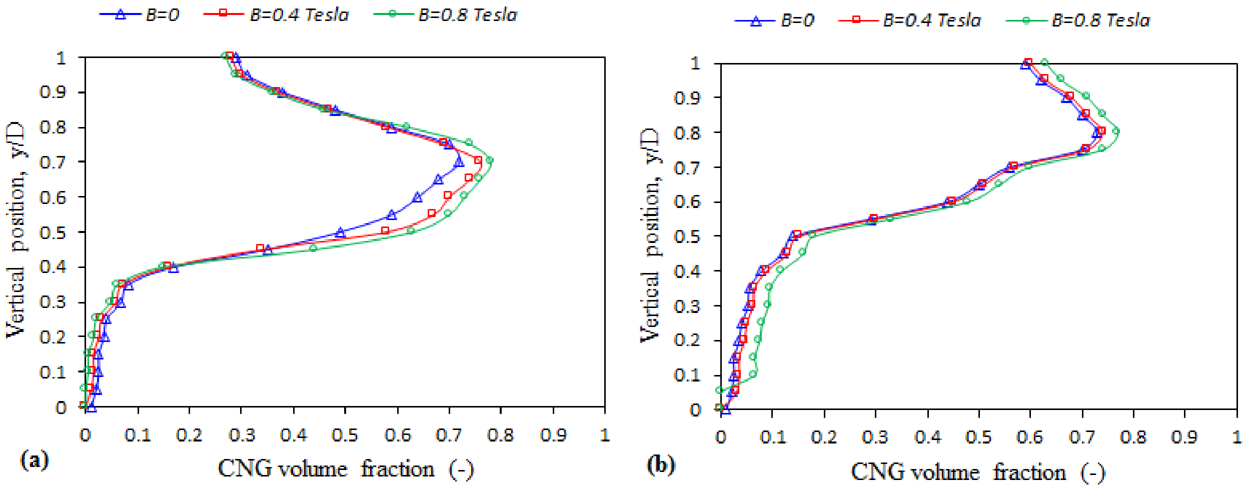


Figure 4: Contours of CNG volume fraction to Diesel-CNG bubbly flow at (*B* = 0.4 Tesla) and during different times: (a) 0.1 sec, (b) 0.3 sec, (c) 0.5 sec, (d) 1.0 sec, (e) 1.5 sec

Figure 5 shows the comparison of the predicted CNG volume fraction profiles at three different positions (a: *x/L* = 0.4, b: *x/L* = 0.65, c: *x/L* = 0.85) with changing magnetic field intensity (*B* = 0, 0.4, 0.8 Tesla). It can be seen from the results, presented in figures 5a, b, and c that the local CNG volume fraction profile shows a peak at the upper part of the pipe, where the gas bubbles tend to migrate toward the upper wall. This behavior increased with the increasing the magnetic intensity. Comparing the results in figure 5 (a), at *x/L* = 0.4, with results shown in figure 5b and 5c, at *x/L* = 0.65 and 0.85, respectively, it is clear that the tendency of bubble motion to the upper part of the pipe is higher. This peak can be attributed to the increased hydraulic resistance of the liquid path between the bubble and the wall which may cause a sharp decline in volume fraction and increases with increasing the magnetic field effect. A similar observation was made experimentally by Kocamustafagullari and Wang [17], Kocamustafaogullari and Huang [18], and Iskandrani and Kojasoy [19].



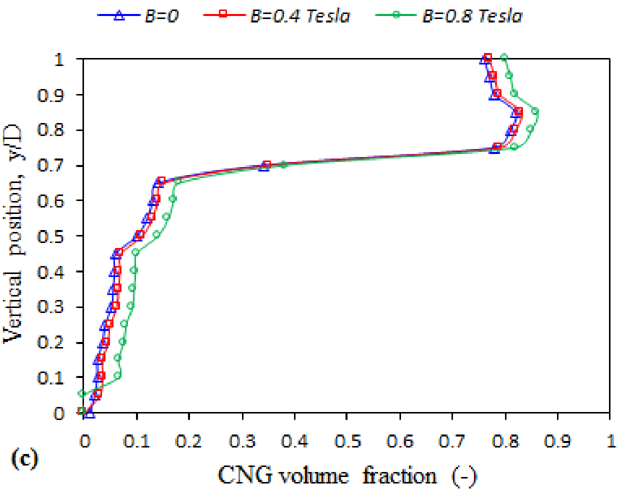
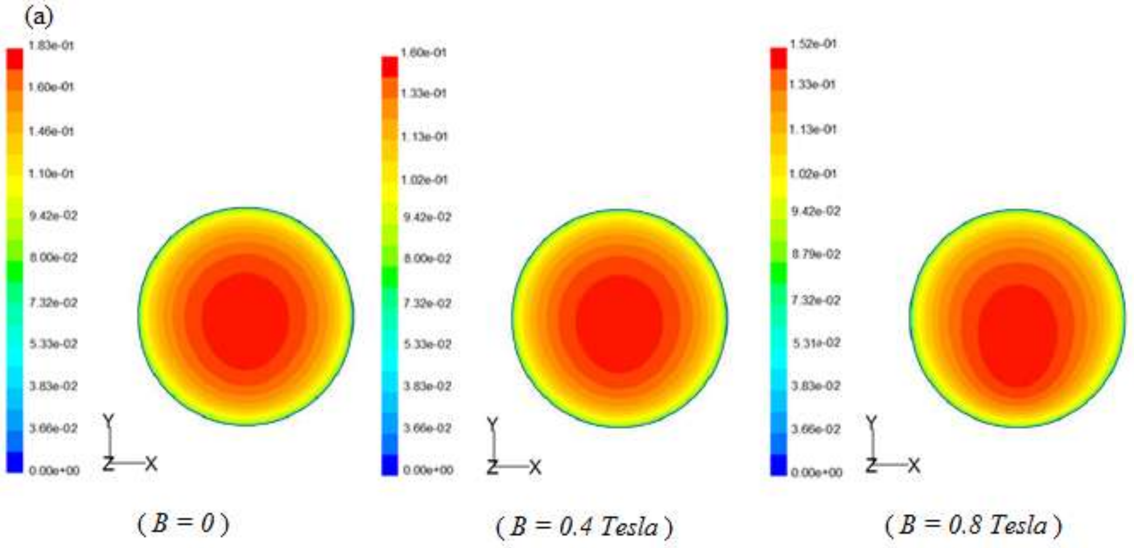


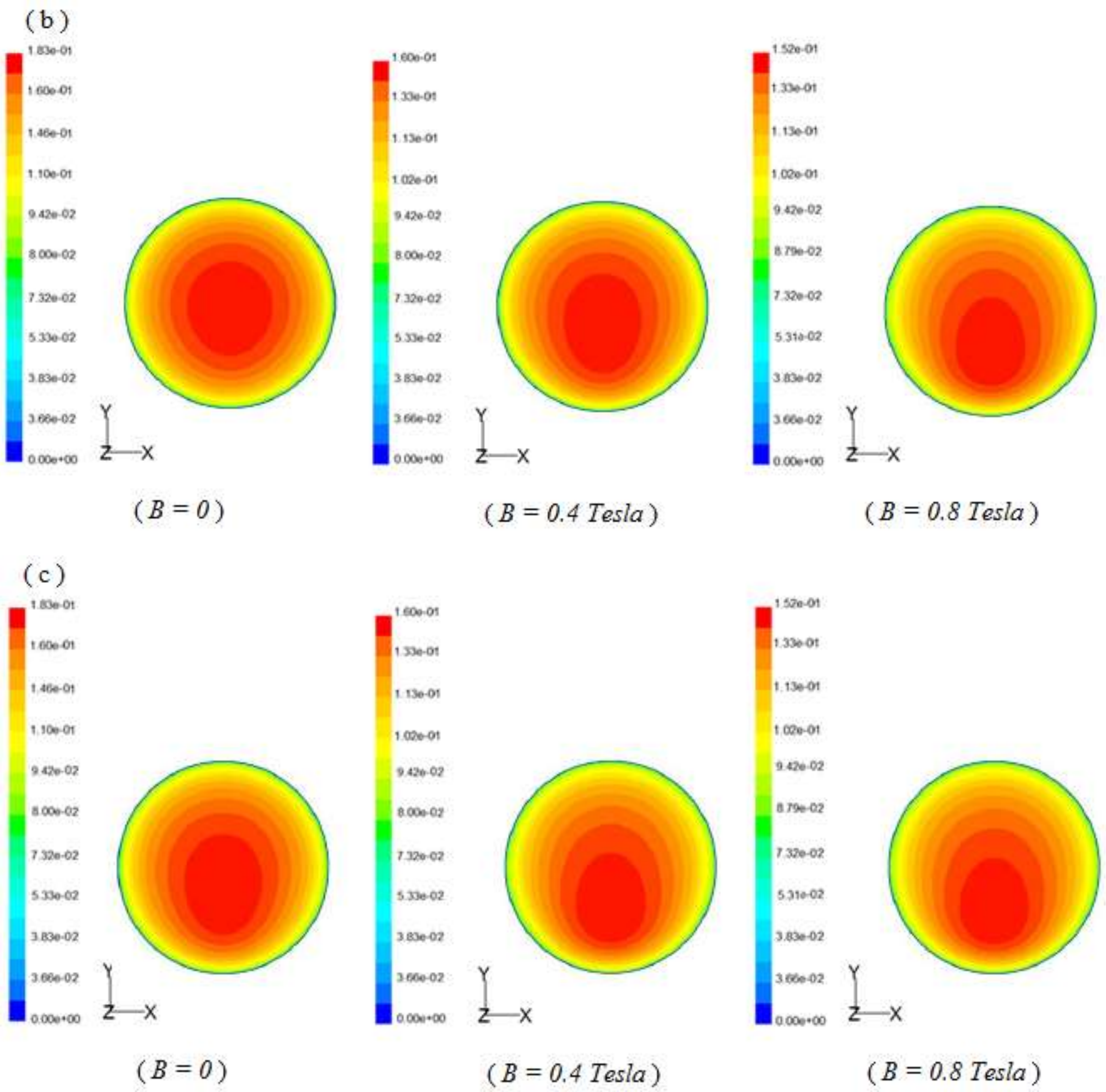
Figure 5: Profiles of CNG volume fraction with vertical position at (*B* =0, 0.4, 0.8 Tesla) and during different location along pipe: (a) *x/L*=0.4, (b) *x/L*=0.65, (c) *x/L*=0.85

3.2 Effect of magnetic field on Diesel axial velocity

Firstly the results showed, axial velocities for diesel in bubbly flow system are greater than those in single phase flow system under the same flow conditions (when the fixed axial diesel velocity in inlet was 0.175 m/sec for all tests under study) due to the inertial force acting between the gas and liquid phases. Since the liquid phase flow occupied a dominant position in the bottom section of the pipe, an interesting feature of the radial velocity profiles was the close resemblance to a fully developed laminar flow irrespective of the gas velocities. According to Kocamustafaogullari and Huang [18] liquid velocities were found to be only slightly greater than the velocities of the gas bubbles. The gas bubbles were accelerated by the liquid inertia in a very short distance after injection but downstream of the bubbly flow, the local gas phase velocities followed closely the local liquid phase velocities. Figure 6 shows cross-sectional contours of the axial diesel velocity at (*B* = 0, 0.4, 0.8 Tesla) and at different locations along the pipe: (a) *x/L*=0.4, (b) *x/L*=0.65, (c) *x/L*=0.85.



(*B* = *0*) (*B* = *0.4 Tesla*) (*B* = *0.8 Tesla*)



($B = 0$) ($B = 0.4$ Tesla) ($B = 0.8$ Tesla)

($B = 0$) ($B = 0.4$ Tesla) ($B = 0.8$ Tesla)

Figure 6: Cross-sectional contours of the axial diesel velocity at (B = 0, 0.4, 0.8 Tesla) and at different locations along the pipe: (a) x/L=0.4, (b) x/L=0.65, (c) x/L=0.85

Figure 7 shows the comparison of predicted axial diesel velocity profiles for different values of magnetic field intensity (B = 0, 0.4, 0.8 Tesla) and at different locations along the pipe: (a) x/L = 0.4, (b) x/L = 0.65, (c) x/L = 0.85. If only a single liquid phase moves in the pipe, the liquid velocity in the pipe top region will be equal to the velocity in the bottom region, exhibiting a perfect axi-symmetry. But these results show that the axial diesel velocity profile has a slight degree of asymmetry due to the presence of the CNG flow. The degree of asymmetry changes with changing the position along the pipe to the outlet and at same time the axial diesel velocity decreases with increasing the magnetic intensity. The diesel velocity in the upper region of the pipe is slightly lower than in the lower region. This could be attributed to the larger volume fraction of gas in the upper region which is the reason for the asymmetric distribution of the diesel velocity and this behavior increases at different positions along pipe. The slip velocity, because of the big difference in densities between phases, is an important parameter in characterizing the nature of the two-phase flow, in particular, the bubbly flow. It is evident that the liquid phase occupies a dominant position in the pipe bottom section where the movement of the gas phase is prejudiced by the liquid phase with a little slip velocity between them. Whereas, in the top part of the pipe, there is a large slip velocity, while the axial diesel velocity profile tends to flatness with increasing magnetic intensity and the reason for this big slip velocity is that the gas moves with less limitation by liquid and liquid velocity tends to decrease.

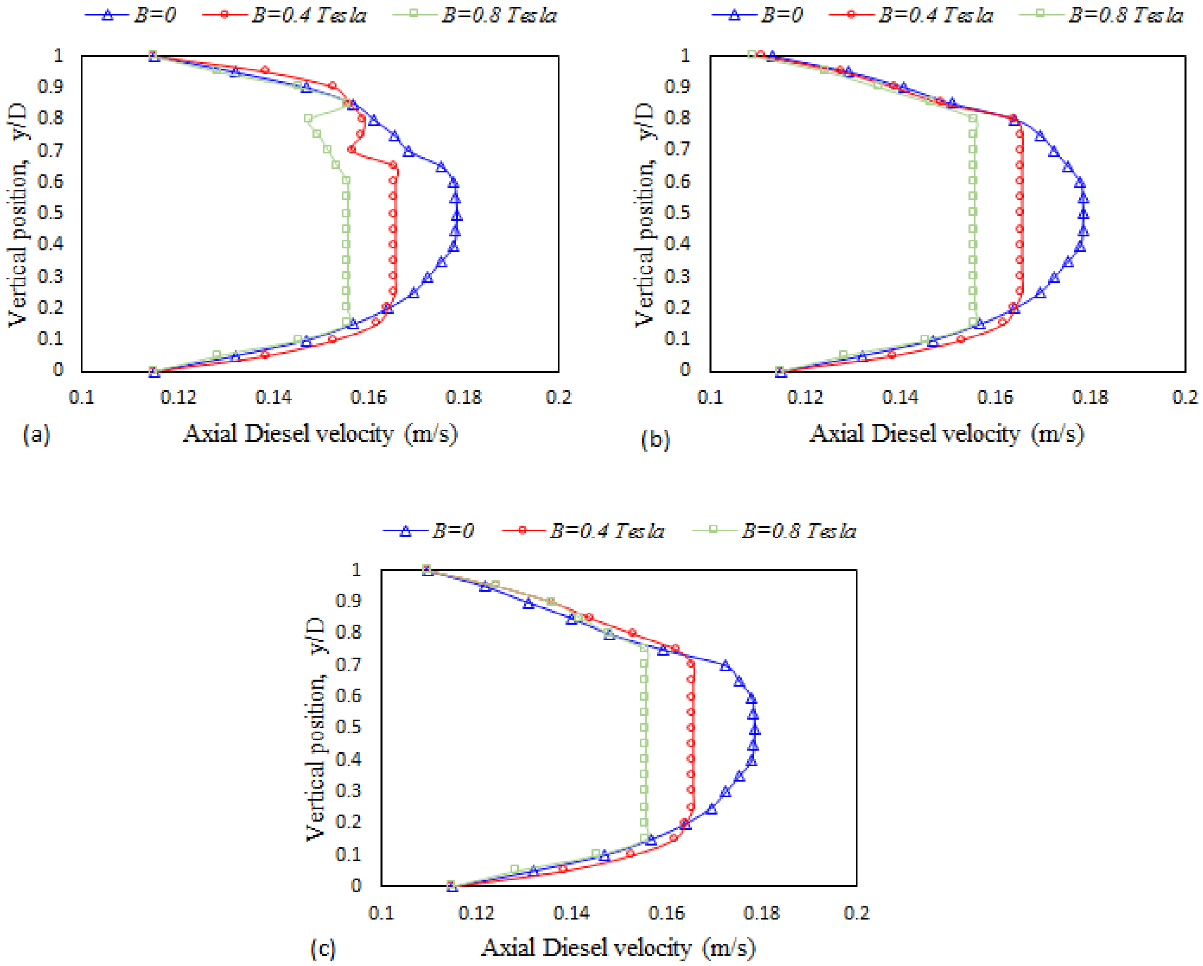


Figure 7: Profiles of axial diesel velocity with vertical position at (*B*=0, 0.4, 0.8 Tesla) and during different location along pipe: (a) *x/L*=0.4, (b) *x/L*=0.65, (c) *x/L*=0.85

The experimental and simulation results reported by Mark et al. [20], shown in Figure 8, are demonstrating that the axial liquid mean velocity showed a relatively uniform distribution except near the upper pipe wall. The flow in the bottom part of the pipe exhibits a fully developed laminar pipe flow profile, whereas in the top of the pipe a different flow exists. These results are broadly agreed with the simulating results obtained for the Diesel-CN bubbly, in the present flow, when the magnetic field strength is equal to zero. On other hand, flatness behavior for fully develop two phase flow and decrease in the axial diesel velocity with increasing magnetic field intensity values obtained in the present simulation are compatible with the experimental results for Malekzadeh et al. [21].

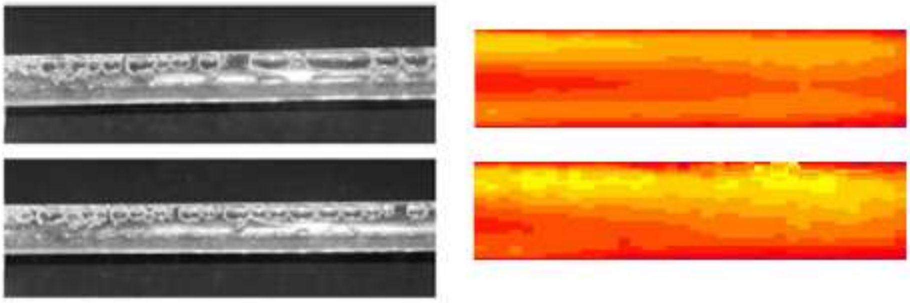


Figure 8: Experimental and simulation results for Mark et al. [20]

4. CONCLUSIONS

The effect of change in intensity of a uniform magnetic field on bubbly flow (Diesel-CNG) in a horizontal pipe has been investigated through computational simulation. The Volume-of-fluid method and three-dimensional incompressible Navier-Stokes equations were used for simulating the motion of CNG bubbles in diesel, in a horizontal pipe flow, under magnetic field effect. The computational results were compared with experimental data from another works in the literature [7, 8], [17-21] and a good agreement was shown. The followings could be concluded from the analysis of the results:

- CNG bubbles tended to migrate toward the upper wall under buoyancy effect and these bubbles grew to a larger volume and expanded in the diesel flow field before they break away.
- Gas volume fraction values increased with increasing magnetic intensity.
- The laminar behavior of the flow changed in the upper zone of the pipe leading to increasing of the gas volume fraction.
- The axial liquid velocity decreased and the profiles tended to flatten with increasing the magnetic field strength.

It is highly recommended to visualize the CNG injection in liquid diesel flow in a horizontal pipe under the effect of various magnetic field strengths.

5. ACKNOWLEDGEMENT

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