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CHARACTERIZATION OF ORIFICE GAS FLOW THROUGH A TUBULAR, COATED CONSUMABLE WELDING ELECTRODE BY CFD ANALYSIS

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ABSTRACT: *Employing tubular coated consumable welding electrodes by modifying the conventional shielded metal arc welding (SMAW) is a recently developed concept aimed to make the welding process towards more environmentally friendly by eliminating organic cellulose in the flux coating. The modified process named as Plasma Enhanced Shielded Metal Arc Welding (PESMAW) employs controlled orifice gas flow through the tubular electrode which is a key parameter for the process to achieve the objectives of its development. In this study, tubular electrode flow channel model was generated and simulated to investigate the fluid flow characteristic with multiple volume flow rates. Two orifice gases, Argon (Ar) and Carbon dioxide (CO_2) were considered for the study and a commercial finite element tool for Computational fluid dynamics (CFD) was used. The velocity profile at each point on the entire length of the electrode at fully developed region was identified with in the fluid flow stream and the development from Laminar to Turbulent flow was also observed. The standard identification method of theoretically computing the Reynolds number (Re) was adopted an*
d the simulated results were compared with the theoretically calculated results for validation.

KEYWORDS: Plasma enhanced shielded metal arc welding (PESMAW); Tubular coated electrode; Laminar flow; Reynolds number (Re).

1.0 INTRODUCTION

Fabrication by welding is one of the most common methods used for ferrous metal joining in the field of manufacturing engineering. Shielded metal arc welding (SMAW), by far the most widely employed welding technique by the engineering industry for various types of manufacturing, is proven to be a highly effective method in terms of low cost and for a relatively simpler usage [1]. The presence of flux coating with a composition of several toxic chemicals over the electrode makes the process to be more environmentally unfriendly as the coated flux chemicals emanate toxic gasses and metal fumes towards the welder as well as into the atmosphere during welding [2]. Attempts have been made hence by various researchers to make the fusion welding process more eco friendly by eliminating several harmful elements that include silicate minerals, cadmium, lead, mercury etc., as well as by introducing new materials and methods [2]. The Plasma enhanced shielded metal arc welding (PESMAW) [3-4] a modified version of conventional shielded metal arc welding (SMAW) process, which uses the tubular coated welding electrode is one of such attempts aims to reduce/eliminate the organic cellulose from the flux coating of cellulosic electrode (EXX10) which are predominantly used in pipeline welding. The reduction/elimination of cellulose from the flux coating serves two main purposes in terms of environmental concerns and the weld metallurgy [3]. The environmental concerns of using cellulose is well known and metallurgically, the diffused hydrogen from cellulose decomposition during welding has been proven to be the root cause for the infamous hydrogen induced cold cracking (HICC) which demands huge inspection costs and sporadic fatal failures. A compensating equivalent to the cellulose, according to Pandey et al. [4], is the supply of auxiliary gas at a controlled volume flow rate to generate laminar flow through the the tubular electrode (shown in Figure 1) into the induced electric arc during welding. It is well known that the laminar flow of gas through a pipe follows parabolic velocity profile [5] .The velocity at the centerline of the pipe is highest and the pressure will be lowest in the fully developed regions. The maximum pressure on the walls due to the zero velocity will tend to constrict the arc, which will lead to the formation of fully ionized plasma [3-4].The ionized gas produces a number of effects. Firstly, it increases the heat input of the arc further and hence the arc energy by increasing the weld pool temperature, which changes the mode of metal transfer, even at comparatively low currents. Secondly, the gas broadens the arc, makes the heat input distribution broader. This will change the surface tension gradients on the weld pool and thereby alter the fluid flow [4]. Moreover the centerline velocity of the orifice gas accelerates the flow of molten metal globules that increases the impact forces thereby depresses the center of the weld pool further that results in deep penetration. The fluid flow characteristics through the tubular electrode therefore, is extremely important for PESMAW process. Since the PESMAW process is a new, novel concept, and the modeling, computation of flow characteriscs of the internal fluid flow through its tubular electrode has no predecessors, there are virtually no such work has been reported in the literature. The objectives of the present study are therefore to predict, identify and analyze the flow characteristics of selected orifice gases by using computational fluid dynamics (CFD) modeling and simulation and validate it by comparing with the standard fluid flow formulae based results. This study also aims to validate part of the fundamental theory of the PESMAW process as well.

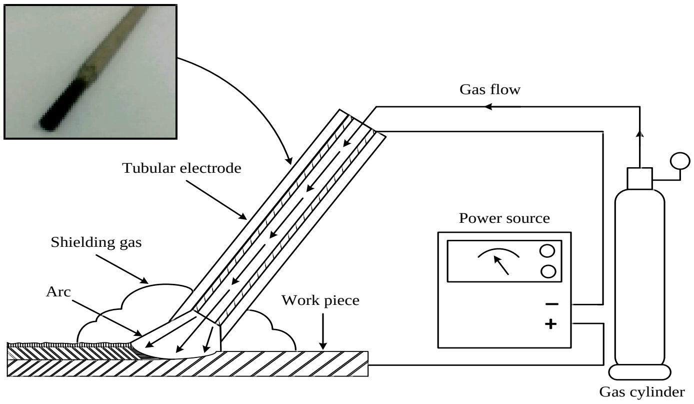

Figure 1: Tubular welding technique and fluid flow in the tubular welding electrode

2.0

3.0 MODELLING OF LAMINAR FLOW CHARACTERISTICS

Most of the published studies on modeling and simulation of laminar fluid flow characteristics and measurement are concerned with the macro dimensional scale. Details of such studies can be found in [5-6]. The importance of meshing grid size in achieving greater accuracy in prediction of flow characteristics was also widely reported in [6,10] studied the entrance length flow simulation using various meshing sizes (grid size) at a circular pipe in laminar and turbulent flow. The compared results of single and multi grids with various mesh grid size on axial and radial distance of circular pipe showed that the multi grid produced a least computation time and a reasonably accurate prediction of fully developed laminar and turbulent flow characteristics. A similar conclusion is reported from the numerical study with variety of mesh grid sizes on laminar flow entrance length in a straight circular a pipe [7]. The prediction of entrance length was carried out by employing CFD Fluent V6.2 with a 2D axisymmetric model being applied under incompressible flow conditions. On the other hand, the fully developed laminar flow characteristics that influences the velocity profile gradient in the horizontal pipe are generally studied by Laser Doppler velocimeter (LDV) measurement technique [8] .For the present work the centerline maximum velocity of the parabolic laminar flow was considered as two times of an average velocity at the fully developed region.

4.0 OPTIMIZATION OF MESHING ON 3D SOLID AXISYMMETRIC MODEL

Meshing of computational model is an important step for finite element based simulation work such that it plays a significant role in obtaining the accurate prediction results. For this study, a mesh analysis was conducted to analyze the accuracy of meshing on the generated 3D solid model by comparing the fluid flow results obtained from the model through CFD analysis with the actual results calculated from the analytical based fluid mechanics theory. A 3D axisymmetric solid model was generated and the mesh analysis on the model was simulated by using a commercial computational fluid dynamic (CFD) software package. The generated 3D solid axisymmetric model with dimensions such 170 mm length and 1.8 mm of internal diameter based on the newly developed tubular welding electrode. The boundary regions for the developed model was considered as inlet, pipe wall ,symmetry and outlet. For the analysis part, several mesh grid sizes were employed and tested for the accuracy of simulation results generated by the CFD tool, such that the most accurate mesh will be selected to proceed further for main flow characterization simulation study. The radial grid size range was varied from 25 to 150 and the axial grid size was selected as 1000. Since the gas properties such as density and viscosity of air are very significantly close to Argon and Helium, the actual gases used for the present simulation work, air was used as the fluid medium for the mesh analysis with a density at 1.225 kg/m^3 and viscosity 1.7894 x10^{-05} kg/m.s respectively. Velocity inlet V_{in} for the entrance region of the flow was calculated by using the standard fluid mechanics theory and was applied 3.27 m/s as the input parameter for all mesh grid sizes. For the simulation analysis, Ansys V14.0 fluid flow was used with second order upwind as spatial discretization [9]. The x and y-velocity was set at 1.0x10^{-6} (solver scale) for residual equation all mesh grid size tests and the double precision solver was adopted under prescribed conditions [8]. The accuracy of grid size was evaluated by comparing the simulated velocity outlet *Vout*, obtained from the outlet boundary region with the calculated input parameter V_{in} .It is well known, according to the theory of fluid flow, for a straight pipe, the velocity outlet will remain unchanged if the area of pipe remains constant, when the frictional and other loses were considered neglected. A Similar assumption was made in this work and the tubular electrode was considered as a smooth pipe and all the frictional and other losses were considered neglected. It was observed that among the majority of the grid size range available from ANSYS software, (25-150 radial at a constant 1000 axial), the optimum percentage error between simulated V_{out} as compared to the V_{in} was recored only at "default mesh" (the grid size is not provided by the software). The ANSYS default mesh recorded with a optimum 2.0% error.

5.0 FLUID FLOW ANALYSIS BY EMPLOYING 3D SOLID AXISYMMETRIC MODELLING

For the fluid flow characterization study, the 3D axisymmetric model that was generated for the mesh analysis was re-employed. The study was conducted in three stages as follows: a) development of 3D axisymmetric model; b) conducting the CFD simulation so as to identify the flow characteristics for the selected orifice gases and c) comparison and validation of the simulation results with the theoretical data.

4.1 Development of 3D axisymmetric model

The 3D solid axisymmetric model was generated in accordance with the specification given and the model was reoriented to a 45° inclination to the horizontal which represents the welding base plate in real conditions. With the geometry drawn and set at zero coordinate, the inclined angle adopted in the model was a mere representation of electrode holder during the experimental setup for plasma shielded metal arc welding (PESMAW) [3-4]. The default mesh grid size with 15176 nodes and 10279 elements was applied to the simulation model based on the mesh analysis. All the boundary conditions that were used during the mesh analysis were kept same as previously prescribed, except the type of fluid medium used. By using the standard fluid mechanics principles, as given in Eq: 1 till 5 are used to generate the input data for simulation in the 3D axisymmetric model.

$$Q = \frac{(\Delta P - \rho g L \sin\theta)\pi D^4}{128\mu L} \qquad (1)$$

The volume flow rate (Q) is calculated with pressure difference (ΔP) in Pa, gas densities *(ρ)* for Ar (1.6228 kg/m^3) and CO_2 (1.7878 kg/m^3) with viscosities, Ar (2.125e-05 kg/ms)' and CO_2 (1.37e-05 kg/ms) were considered respectively. The velocity inlet is given as

$$V_{avg} = \frac{(\Delta P - \rho g L \sin\theta)D^2}{32\mu L} \qquad (2)$$

Where L and D are the length and diameter of axisymeteric model respectively. The simulation was carried out at a 45° orientation (θ). The Reynolds number and pressure difference at the model is given by

$$R_e = \frac{\rho . V_{avg} . D}{\mu} \qquad (3)$$

$$\Delta P = \frac{128\mu L Q}{\pi D^4} + \rho g L \sin\theta \qquad (4)$$

The maximum velocity at fully developed flow is calculated and is given in Eq: 5

$$u_{\max} = 2V_{avg} \qquad (5)$$

The volume flow rate for this study are selected in the range 0.5 till 5.0 L/min with increment of 0.5 L/min. The fluid flow was characterized with Reynolds number (*Re*) range (2300 >*Re* > 4000) [8,10].

4.2 CFD simulation on the 3D-axisymmetric model

Simulation on the 3D-axisymmetric model was carried out following the five standard stages of procedure such as geometry, meshing, setup physics, solution and results [10-11]. The 3D axisymmetric model was generated in accordance with the specifications of E60XX tubular coated electrode used in PESMAW. The generated model was meshed with an optimum mesh grid size as per the results from the previously discussed mesh analysis with boundary domains. The Velocity inlet V_{in} from volume flow *(Q)* rate applied as input parameters in the inlet boundary region with other flow physics factors. The solution with standard initialization was adopted and applied to the respective orifice gases. Finally the result of fluid flow occurring through the model was identified. The flow pattern, velocity outlet and maximum velocity outlet were gathered at the outlet boundary region. From the results, the flow in the tested model was found to be in hydrodynamically developing and fully developed flow with zero velocity at the electrode wall and the maximum velocity at the centerline of the flow.The contour image of the flow stream with simulated data obtained from the simulation is shown in Figures 2 and 3 .

6.0 RESULTS AND DISCUSSION

The CFD based simulated data and graphical contour results from the study on an 1.8mm inner diameter 3D solid axisymmetric model which represents the tubular consumable welding electrode in PESMAW process confirmed that the volume flow rate plays a major role in determining the flow characteristics of the tubular electrode. The graphical contour charts clearly identified two types of flow region such as developing and fully developed region occurred in the electrode tube. Both results were in good agreement with the theoretically calculated results. Moreover, the results confirmed the established fact of the importance of Reynolds number at each tested volume flow rate, such that it solely affects the development of flow region in the model. Also the entrance length of Ar and CO_2 was clearly found to be differing at similar volume flow rates, attributable to the different gas properties mainly the gas density and viscosity. It was found from the results that the optimum volume flow rate that would cause the desirable fully developed laminar flow were 1.0 L/min and 1.5 L/min for CO_2 and Ar respectively.

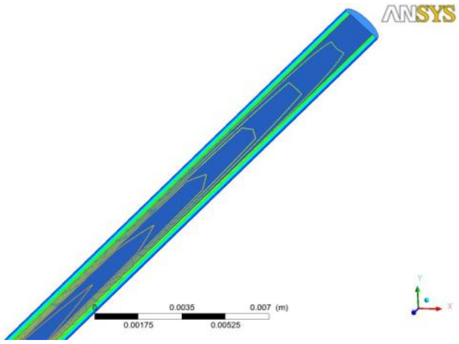

Figure 2: Flow stream at incline 45 °of Ar of volume flow rate 1.5 L/min

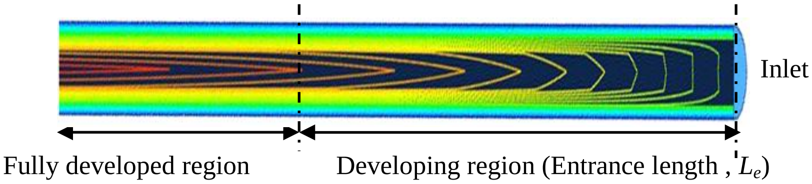

Figure 3: Hydrodyanamic developing and fully developed region in 1.8mm diameter on 3D solid symmetrical at 1.5 L/min of Ar

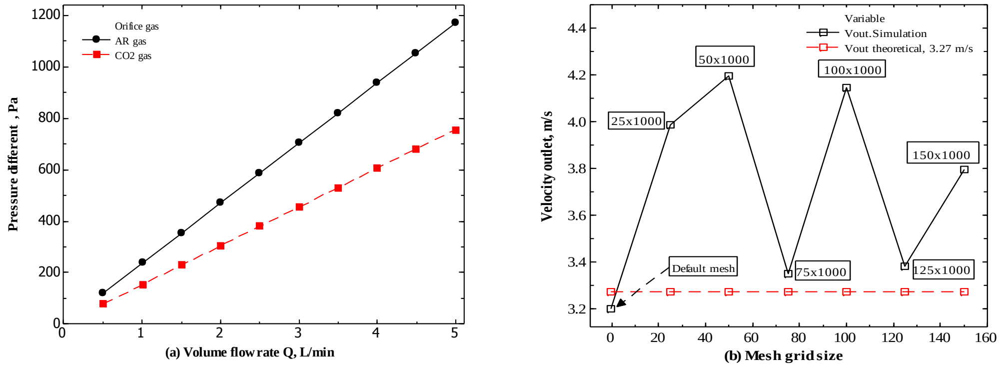

Figure 4: (a) Variation in pressure diference for the 3D axisymmetric model for Argon and Carbon dioxide.(b) Mesh analysis for optimum mesh grid size.

Figure 5 shows the velocity profile for Ar and CO_2 under the prescribed flow rates. For Ar, laminar flow seemed to be occurring within the flow rates from 0.5 to 2.5 L/min. However, the flow was inside the fully developed region only between 0.5 to 1.5 L/min and from 2.0 to 2.5 L/min the flow occurred inside the developing region where laminar gas flow achieved the highest center line velocity. For CO_2, the laminar flow occurred in comparatively low flow rates such as 0.5 to 1.0 L/min and the flow is formed at the fully developed region. One of the possible reasons for this occurance could be the density of Ar (1.622 kg/m^3) lighter than CO_2 (1.788 kg/m^3) as Ar flows much faster than CO_2 gas such that the maximum velocity at 1.0 L/min flow rate Ar recorded 12.902 m/s and CO_2 at 12.720 m/s. It was also found that the flow rate also influenced the pressure difference in the flow region for both gases such that Ar recorded a higher pressure different as compared to CO_2 as shown in Figure 4 .This can be attributed to the difference in flow velocity which on the other hand related to the individual gas properties.

The simulated results of velocity outlet for Ar and CO_2 were compared with the theoretically calculated results and the percentage error between the two results were calculated to evaluate the accuracy of the simulated results, shown in Figure 6. It was found that the simulated results are in good agreement with the theoretical results with percentage error between 1-3. The selection of optimum mesh grid size from the preliminary mesh analysis with default mesh grid size (Figure 4) with element and nodes (10279, 15176) thus proven to be beneficent to produce a close results on the 3D axisymmetric model.

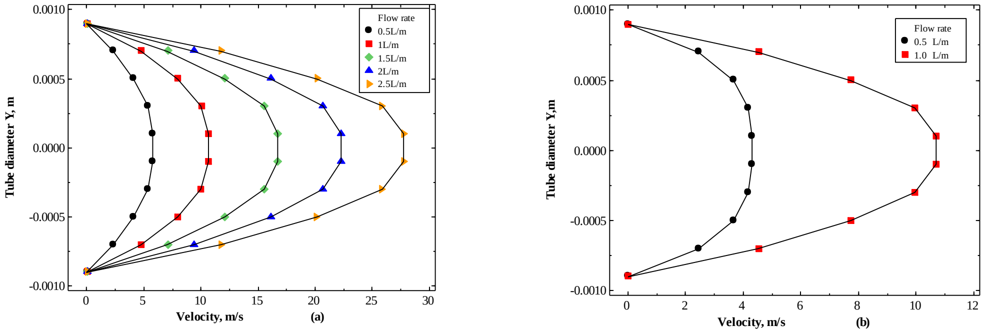

Figure 5: The Laminar flow pattern of maximum velocity of fully developed region in 1.8mm diameter of 3D axisymmetric for Ar (a) and CO_2 from CFD simulation.

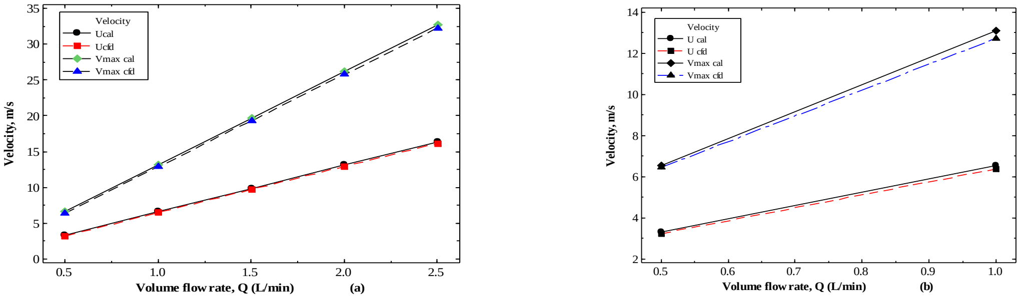

Figure 6: Comparison results of theoretical and CFD simulation of velocity outlet and maximum velocity on Laminar flow condition for Argon (a) and Carbon dioxide gas (b) in 3D axisymmetric model

6.0 CONCLUSION

For two gases Ar and CO_2 when flow through the orifice of a 1.8mm diameter tubular electrode at incompressible and steady states, the gas flow analysis was conducted by employing FEM based CFD modeling. The simulated results were validated by comparing with the data calculated by using basic fluid mechanics theory. It is concluded that the finite element based CFD method proven to be one of the best tools for modeling, simulation and analysis of the fluid flow through a reasonably smaller diameter tubes [4,6]. The simulated results of the 3D solid axisymmetrical model with the optimum mesh grid size are in good agreement with the theoretically calculated results. For Ar and CO_2 at volume flow rates of 2.5 and 1.0L/min, the optimum velocity outlet were found to be at 16.142m/s and 6.360m/s respectively. These simulated results were found to be much closer to the theoretically calculated velocity outlets for Ar at 16.370m/s and 6.550m/s respectively.The volume flow rate plays an important role in the flow development through the tube such that: (a) an increment of volume flow rate that influences the Reynolds number resulting in the formation of laminar flow in the developing region with the maximum velocity at the center line of the parabolic velocity profile for both Ar and CO_2 gases; and (b) the increase in volume flow rate also found to be increasing the entrance length in direct proportionality for both gases. Three types of flow such as laminar,transition and turbulent were found to be occurring in the tube between the tested range of volume flow rates (0.5 to 5.0 L/min) within the developing and fully developed regions, for both orifice gases. At fully developed region the laminar flow was found to occurring within the volume flow rate range of 0.5-1.5 L/min for Ar and for CO_2 the range was from 0.5-1.0L/min.

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