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# NUMERICAL SOLUTION OF A THERMAL AND FLUID-DYNAMIC PROBLEM INVOLVING PHASE CHANGE WITH MOVING SOURCE APPLIED TO TIG WELDING PROCESS

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**Abstract.** *The numerical solution of advective-diffusive thermal problems have been the theme of countless scientific papers. The proposal of this study is to simulate computationally the fusion and solidification of metals.. The dimensions and the shape of the weld bead denotes if the welding was applied satisfactory or not. During phase change, combined effects related to the thermal gradients, fluid-dynamics, just as gravitational and electromagnetic forces surely have strong influence on the welding pool formation. This study aims to conceive and implement computationally a thermal/fluid-dynamic model with phase change and moving source. From mathematical and computational methods and available scientific literature database it was defined an advective-diffusive thermal model. Concepts involving fixed mesh and techniques for the coupling of involved equations, as well as the solution of the nonlinearity inherent to phase change, were also themes of this work. The proposed models were validated singly and together using softwares such as MatLab and OpenFOAM. Thereunto, experimental data and information available on scientific literature were used. The results obtained demonstrate that the joint solution for the thermal/fluid-dynamic problem with phase change provides a better comprehension of the welding pool formation process.*

**Keywords:** *welding, phase change, moving source, energy, Navier-Stokes.*

## 1. INTRODUCTION

Phase change problems are characterized by the presence of a free boundary that travels over time, i.e. the solid / liquid interface and liquid / solid that changes during welding. From the mathematical point of view, it is a completely non-linear problem, in which the position of the fusion interface, as well as the physical properties for each phase, continuously changes. In this sense, numerical techniques become an attractive way to obtain solutions of physical problems and practical interest such as welding.

The present work aims to design and implement computationally a thermal / fluid dynamics model with phase change. From mathematical / computational methods and data available in the scientific literature will be designed two-dimensional thermal models for the study of advective / diffusive problems. By means of such models, it is expected to study and evaluate the combined effects involving high thermal gradients, phase transition, fluid dynamics, gravitational and electromagnetic forces in the formation process of the melt pool.

For the validation of the models proposed in this work, experimental data were used in the scientific literature. The results showed that the combined solution of the mathematic thermal/fluid-dynamic problem with phase change provides a better understanding of the melting pool formation process during metal welding. And what future work should be directed towards such a practice.

## 2. THERMAL WELDING PROBLEM

The objective is to simulate the heating and phase change of the AISI 304 steel during the TIG welding process. The welding problem is the same as that studied by Cângani (2010), however in this work a more complete approach will be applied including a fluid dynamics analysis of the welding pool.

This is a three-dimensional problem in which the convection effect at the lateral and lower borders is considered. At the upper boundary, there is the effect of free convection and static heat flux (centered on the y-axis) generated by the TIG welding torch.

From the mathematical point of view, the problem can be considered symmetrical, which allows the use of a two-dimensional thermal / fluid dynamics, significantly reducing the computational cost.

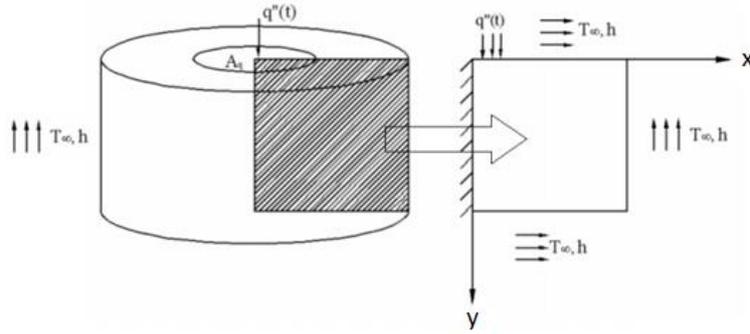


Figure 1. Welding problem. Adapted of Cângani (2010).

Some considerations are taken in approaching the problem, such as: welding occurs without material deposition and the heat source is static. The coefficient of convective heat transfer was considered constant. The mathematical model was based on Brent and Voller (1988). The Equation 1 models the thermal part and Eqs. 2 to 4 the fluid dynamics.

$$\rho c \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - \rho L \frac{\partial f}{\partial t} \quad (1)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (2)$$

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho} \frac{\partial P}{\partial x} - \left( u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) + \nu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + S_u \quad (3)$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho} \frac{\partial P}{\partial y} - \left( u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) + \nu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \rho_{ref} g \beta (T - T_{ref}) + S_v + F \quad (4)$$

The terms  $S_u$  and  $S_v$  present in Eqs. 3 and 4 are source terms to account for the velocity suppression. According to Carman-Kozeny by Voller and Prakash (1987), during the solution process of the momentum field, the velocity at the computational cell located in the solid phase should be suppressed while the velocities in the liquid phase remain unaffected. One of the popular models for the velocity suppression is to introduce a Darcy-like term:

$$\vec{S} = -C \left( \frac{(1-f)^2}{f^3 + b} \right) \vec{V} \quad (5)$$

where  $C$  is a sufficiently large constant to dissipate all velocity when the cell becomes solid.  $\vec{V}$  is the velocity vector and  $b$  is a very small constant, used only to prevent division by zero in cases where the cell is in the solid state and the mass fraction is zero.

Natural convection effects are treated with the Boussinesq model (BRENT and VOLLER,1989), which takes into account the density change according to the temperature of the material. Such expression is evaluated as a source term in the linear momentum equations.

The term  $f$  represents the mass fraction that is the fraction of liquid that arises during the phase change.

During phase change the combination of effects related to high thermal gradients, fluid dynamics, as well as gravitational and electromagnetic forces, certainly has strong influence on the formation of the welding pool. The present study aims to evaluate the influence of the term  $F$  and to verify its influence on the geometry of the welding pool. It is emphasized that gravity will be positive when following the direction of the  $y$ -axis as shown in Fig. 1. Therefore, we adopt  $F$  positive to act in favor and negative  $F$  to act against the gravitational effects.

Table 1. presents experimental data adopted in this work based on Cângani (2010).

Dimensions of the welded work piece	$x = 0.03$ [m] $y = 0.03$ [m]
Welding radius	0.051 [m]
Heat flux supplied to the work piece	$1.9 \times 10^7$ [W/m <sup>2</sup> ]
Welding time	120[s]
Convective heat transfer coefficient	40[W/m <sup>2</sup> K]
Thermal properties (stainless steel AISI 304)	$k = 26$ [W/mK] $c = 650$ [J/kg.k]
Volumetric thermal expansion coefficient	$15 \times 10^{-6}$
Density	7200Kg/m <sup>3</sup>
Melting point	1455°C
Dynamic viscosity	$1.81 \times 10^{-3}$ [Kg/m.s]
Latent heat of fusion	265200 [J/kg]

The CFD code for solving the welding problem was based on an existing OpenFOAM solver called *buoyantPimpleFoam*, specific for solving problems involving transient fluid flow with turbulent, natural or laminar convection

### 3. RESULTS AND DISCUSSION

To verify if the implementation of the geometry, equations and boundary conditions were correctly defined in the software the results obtained from the OpenFOAM were evaluated using the experiment performed by Cângani (2010).

In order to reduce the computational cost, only the heating period of the sheet metal, which comprises the initial 120 seconds of welding, was evaluated. Thus, considering only Eq. 1 and the boundary conditions and phase change effects.

Figure 2 illustrates the comparison between experimental and simulated data according to the position of thermocouples presented in Tab. 1.

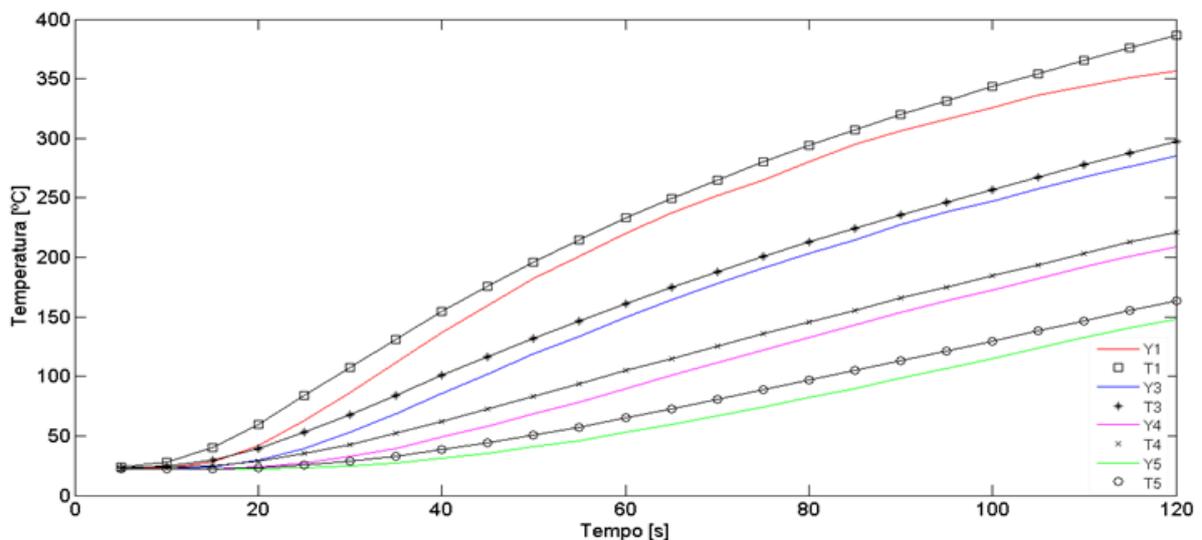


Figure 2. Comparison between experimental( $Y_i$ ). and simulated( $T_i$ ) data according to the thermocouples coordinates: T1 (0.001;0.03) ; T3 (0.017;0.03) ; T4 (0.027;0.03) ; T5 (0.036;0.03)

To simulate the combined influence of gravitational effects and magnetic forces the term of Boussinesq approximation was multiplied by a factor  $F$  as presented in Fig. 3.

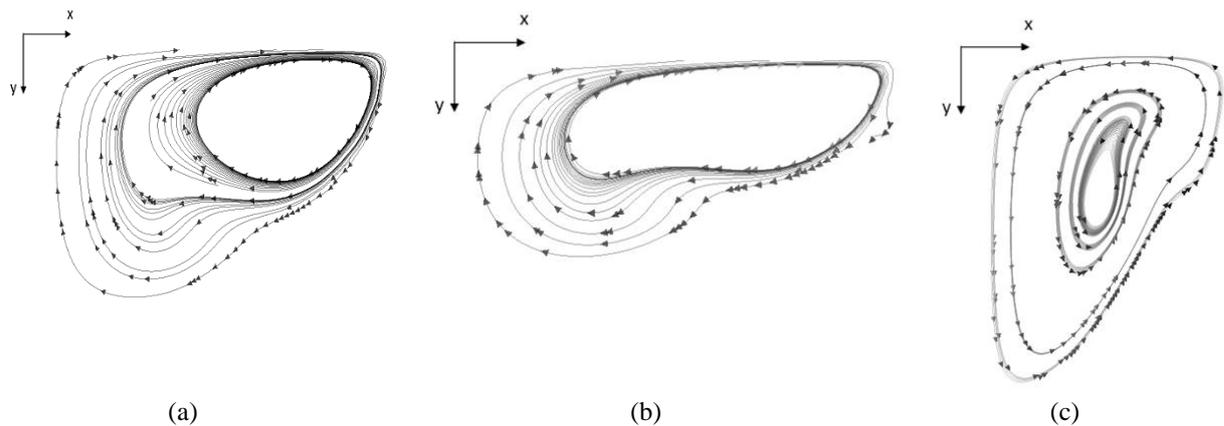


Figure 1. Current lines. (a)  $F=0$ ; (b)  $F$  favorable to gravity; (c)  $F$  contrary to gravity (Miranda,2016).

When  $F$  is favorable to gravitational forces the melting pool tends to rotate clockwise and becomes wider. However, when  $F$  is contrary to gravity the melting pool turns counterclockwise and becomes deeper. Such characteristics demonstrate the importance of the use of a complete thermal and fluid dynamic model in the study of welding thermal problems.

#### 4. CONCLUSIONS

The present work had as purpose to design and implement computationally a thermal and fluid model with phase change. Based on a TIG welding process, experimental temperatures were used to validate the model. Qualitatively, simulated and experimental data presented a good agreement. The results presented in Fig. 3 demonstrate the importance of applying a more detailed thermal / fluid dynamics model for the analysis of the melting pool formation during metal welding. Based on the results obtained, it is proposed in future works to apply the thermal / fluid dynamics model to effectively analyze the influence of electromagnetic and gravitational forces on the formation of the welding pool in TIG welding processes.

#### 5. ACKNOWLEDGMENTS

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