5TH INTERNATIONAL CONFERENCE ON ADVANCES IN MECHANICAL ENGINEERING ISTANBUL 2019, 17-19 DECEMBER 2019

EFFECT OF FLUID FLOW ON MORPHOLOGY AND PROPERTIES OF WELDING

Abdel Halim Zitouni[1,3,*], Mouloud Aissani[1], Pierre SPITERI[2], Younes Benkheda[3], Moustafa Boukraa[1]

ABSTRACT

In this work, the effect of fluid flow on the morphology of the weld pool and the welding properties during Tungsten Inert Gas (TIG) process using 304L stainless steel is investigated. In the first part, a computation code under Fortran was elaborated to solve the equations resulting from the finite difference discretization of the heat equation, taking into account the liquid-solid phase change with the associated boundary conditions. In order to solve the Navier-Stokes equations expressed in the stream-vorticity formulation, a mathematical model was developed to study the effect of the melted liquid movement on the weld joint. The evolution of the fraction volume of the liquid and the thermal fields promoted the determination of the molten zone (MZ) and the Heat Affected Zone (HAT)dimensions, which seems to be in good agreement with literature.

Keywords: *Thermal and fluid modeling, TIG welding, Heat Affected Zone, molten zone, numerical simulation.*

INTRODUCTION

TIG welding is an electrical arc process for assembling. During welding, several physical phenomena occur, such as heat transfer by conduction and convection; these phenomena have great importance on the morphology and size of the weld, as well as on the microstructure of the welded sheet. Indeed, during TIG welding, the weld pool is the seat of a strong thermal gradient, this creates weldability problems due to the appearance of risk zones, noted by MZ for the melted zone and by HAZ for the heat affected zone. These weldability problems correspond to cracking to solidification, cold cracking, residual stresses and distortion [1, 2].

In this work, two-dimensional mathematical model of 304L stainless steel TIG weld without filler metal was described. The heat equation was coupled with the Navier-Stokes equations where only the stream vorticity formulation of the equations governing the fluid in the weld pool was considered, due to the non-linear formulation of Navier-Stokes equations. This work is organized as follows:

In the first case, the thermal problem was studied without considering the movement of molten metal and convection in our calculations, only the mode of heat transfer by conduction has been taken into account.

In the second case, the movement of the molten metal in the weld pool is studied in order to evaluate its effect on the morphology and the size of the weld pool when the surface tension gradient is negative, on the other hand, in the heat equation we add the convection transfer mode in our calculations.

Finally, the same study as the second case is conducted considering a positive surface tension gradient.

MATHEMATICAL FORMULATION

Equation of heat

Taking into account the presence of a solid-liquid phase change, the heat equation in cylindrical coordinates (r, z) is expressed as follows:

$$\rho C_p\left(\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}\right)-k\frac{\partial^2 T}{\partial r^2}-k\frac{\partial^2 T}{\partial z^2}-\frac{k}{r}\frac{\partial T}{\partial r}=-\rho\Delta H\frac{\partial g_l}{\partial t} \quad (1)$$

where u and w are the components of speed, C_p is the specific calorific ability, k is conductivity, is density, T is temperature, and H is latent heat of fusion. In addition, the liquid fraction is defined by:

$$g_l=\begin{cases}1 & T>T_L\\ \frac{T-T_S}{T_L-T_S} & T_S\le T\le T_L\\ 0 & T<T_S\end{cases} \quad (2)$$

where T_L and T_S are the liquidus and solidus temperatures, respectively. Because of the symmetry during welding, our calculations were conducted only on one single welded piece as shown in Figure II.1.

[1]*Research Center in Industrial Technologies CRTI P.O.BOX 64, Cheraga 16014 Algiers, Algeria*
[2]*IRIT, INP-ENSEEIHT, 2 Rue Charles Camichel 31000, Toulouse, France*
[3]*Département de Génie Mécanique, Université de Blida1, BP 270, Route de Soumaa, Blida, Algérie*
**Correspondance : a.zitouni@crti.dz*

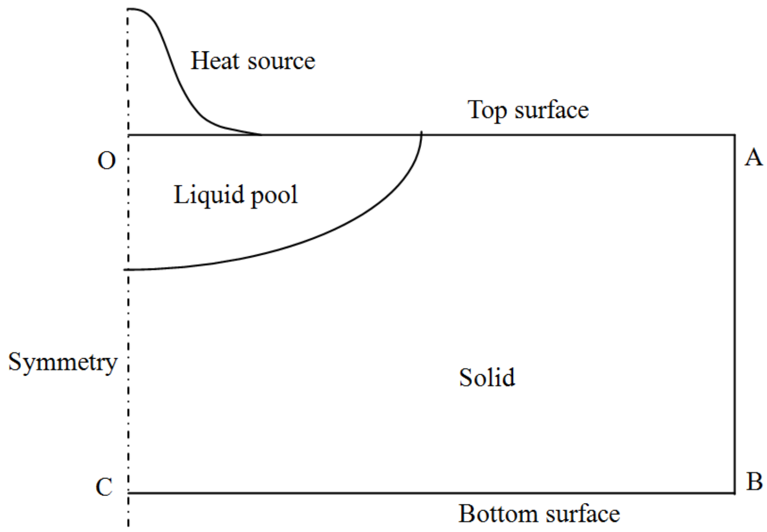

Figure II.1: Schematic of the welding cross section

STREAM VORTICITY FORMULATION OF MOTION EQUATIONS

In the current problem, partial derivative equations are defined in the two-dimensional case. In addition, it should be noted that the resolution of Navier-Stokes equations is very difficult because of the non-linearity present in the model. However, since we consider only the two-dimensional case, the resolution of the Navier-Stokes equations can be simplified taking into account the stream vorticity formulation of the Navier-Stokes equations.
In such a formulation, vorticity is defined by:

$$\omega = \left(\frac{\partial u}{\partial z} - \frac{\partial w}{\partial r}\right) \tag{3}$$

In addition, the current function ψ is expressed by:

$$u = -\frac{1}{r}\frac{\partial \psi}{\partial z} \tag{4}$$

$$w = +\frac{1}{r}\frac{\partial \psi}{\partial r} \tag{5}$$

Using vorticity and stream functions, equations governing fluid dynamics can be easily written as follows:

$$\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial r} + w\frac{\partial \omega}{\partial z} - \frac{u\omega}{r} = \nu\left(\frac{\partial^2 \omega}{\partial r^2} + \frac{1}{r}\frac{\partial \omega}{\partial r} + \frac{\partial^2 \omega}{\partial z^2} - \frac{\omega}{r^2}\right) - \beta g\frac{\partial T}{\partial r} + \nabla \times (\vec{J} \times \vec{B}) \tag{6}$$

$$-\omega = \frac{1}{r}\frac{\partial^2 \psi}{\partial z^2} + \frac{1}{r}\frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r^2}\frac{\partial \psi}{\partial r} \tag{7}$$

In the equation (6) appears an electromagnetic force that can be calculated by the resolution of Maxwell's equations in the coordinates system (r, z); this force is given by the following equation (8) [3].

$$\nabla \times (\vec{J} \times \vec{B}) = \frac{C_0 \mu_0 I^2}{2\pi^2 L r^3}\left(1 - \frac{z}{e}\right)\left[1 - exp\left(-\frac{r^2}{2\sigma_j^2}\right)\right]^2 \tag{8}$$

where C_0 is the length scale factor, I is the welding current, μ_0 is magnetic permeability, σ_j is the current distribution parameter and e is the thickness of the welded sheet.

BOUNDARY CONDITIONS

	Heat equation	Stream Vorticity equation
OA	$-k\frac{\partial T}{\partial z}\Big\vert_{OA} = \frac{Q}{2\pi R_0^2}e^{-(\frac{3r^2}{R_0^2})}$	$\omega\vert_{OA} = -\frac{1}{\mu}\frac{\partial \gamma}{\partial T}\frac{\partial T}{\partial r}$, $\frac{\partial \psi}{\partial r}\Big\vert_{OA} = 0$
AB	$-k\frac{\partial T}{\partial z}\Big\vert_{AB} = h(T - T_0) + \sigma_0\varepsilon(T^4 - T_0^4)$	$\omega\vert_{AB} = 0$, $\frac{\partial \psi}{\partial z}\Big\vert_{AB} = 0$
BC	$-k\frac{\partial T}{\partial r}\Big\vert_{BC} = h(T - T_0)$	$\omega\vert_{BC} = 0$, $\frac{\partial \psi}{\partial z}\Big\vert_{BC} = 0$
OC	$\frac{\partial T}{\partial r}\Big\vert_{OC} = 0$	$\omega\vert_{OC} = 0$, $\frac{\partial \psi}{\partial z}\Big\vert_{OC} = 0$

NUMERICAL RESOLUTION

To solve the coupled problem describing the welding applied on 304L stainless steel sheets; it is required to solve on the one hand, the equation of heat and, on the other hand, the Navier-Stokes equations formulated by the functions of vorticity and stream, since the analytical resolution of Navier-Stokes equations is very difficult to obtain, thus we solve equations (1), (6) and (7) numerically. To find an approachable solution to the welding problem, we will construct a finite difference approximation of the previously obtained governing equations. For the numerical resolution of the problem, spatial discretion is considered using the classic method of finite differences; the dots are numbered in the bottom from the top, then from left to right according to the increasing abscissa. For temporal discretion, we consider, preferably, an implicit time scheme that is unconditionally stable, while an explicit time scheme is conditionally stable which would involve choosing a small time step. The combination of spatial and temporal discretizations leads to the resolution at each stage of time, a non-linear algebraic system, taking into account the phenomenon of radiation on the border (OA U AB U BC).The computational domain is mesh using a regular distribution of nodes by 100 to 50 cells. The convergence criterion was set at a maximum relative error for all dependent variables (ψ, ω, T) less than 10^{-6}. Thus, all the remaining variables can be deduced.

RESULTS AND DISCUSSIONS

The model and program developed is used for the numerical calculation of the temperature field, the velocity field, the fraction of the liquid, the size and morphology of the fusion zone (FZ) and the size of the thermally affected zone (HAZ) during TIG welding operation without metal input in three different cases.

In the first case we calculations are performed with a single thermal transfer mode, which is conduction, without taking into account the movement of the molten metal. The isothermal curves and the fraction of liquid calculated at the moment t=2s are represented on Figure IV.1 and Figure IV.2 respectively. The isothermal curves are very close to each other in the vicinity of the heat source, largely separated away from the source. The different states of the material corresponding to different zones, the latter are predicted by the values of the isothermal curves, in particular the fusion zone (ZF) and the heat-affected zone (ZAT).

At the t=2s, the weld pool at a width equal to 5.6 mm and a depth of about 1.2mm Figure IV.2, or a ratio of P/L=0.21. The width of the thermally affected area (ZAT) is delineated by the isotherms of the melting temperature and these give the eutectoid temperature set at 996 K [4], this width is in the order of 2.2mm Figure IV.1.

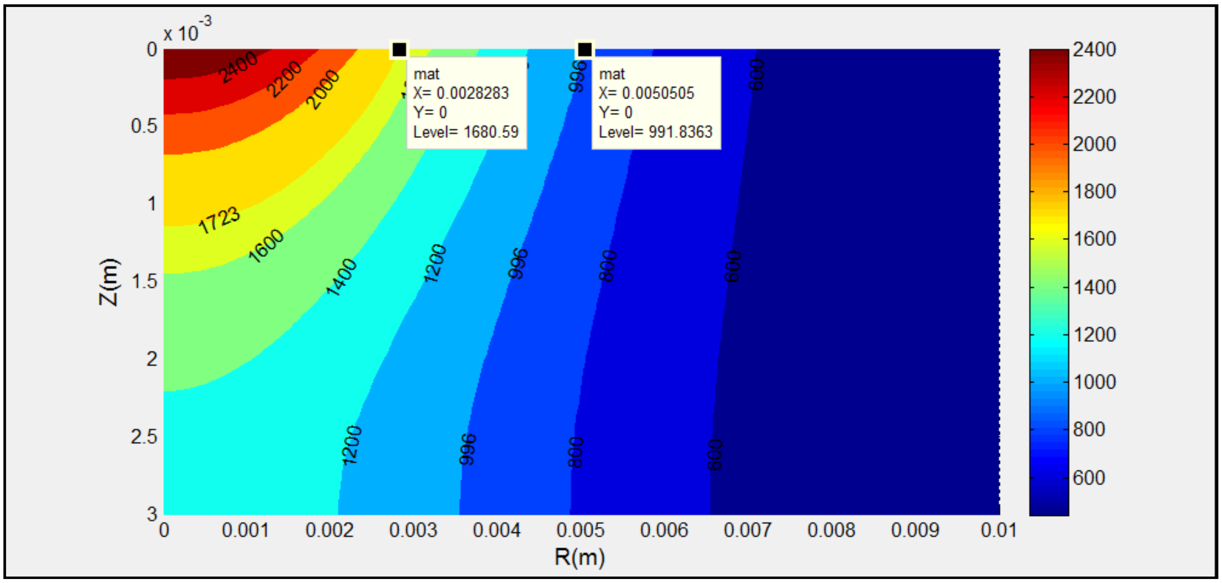

Figure IV.1 : Temperature distribution and isotherms calculated with conduction alone.

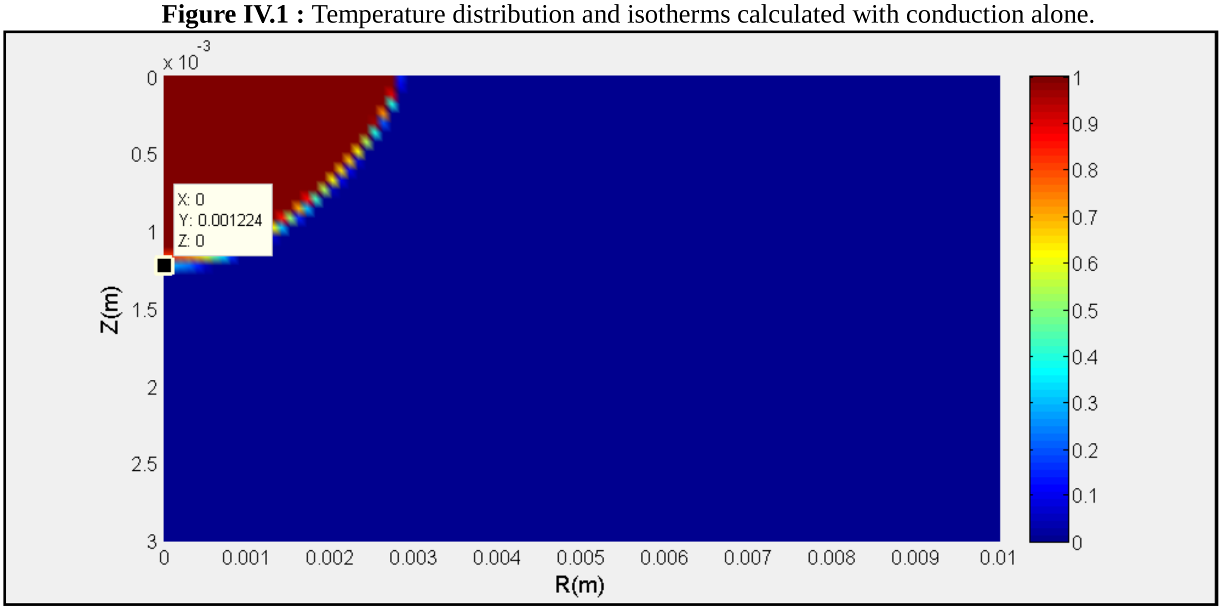

Figure IV.2 : Fraction of liquid calculated with conduction alone.

In the second case we took into account the movement of the molten metal in our calculations, by coupling the heat equation with the Navier-Stokes equations in the stream vorticity formulation. Figure IV.3 represents the temperature distribution and isotherms calculated with a negative surface tension gradient $\frac{\partial\gamma}{\partial T} < 0$ at t=2s. Taking into account the effect of the movement of the molten metal in us calculation, the maximum temperature is higher than that found in the previous case, it is in the order of 2800 K, this is due to the decrease of the exchange area by conduction. The orientation of the speed vectors is outward; the flow in the weld pool surface directs the energy delivered by the heat source outwards, which gives a centrifugal brewing Figure IV.4. The maximum speed calculated in the order of 0.12 m/s [5]. The penetration and width of the weld pool are respectively, P =1.6 mm and L =6.6 mm with a ratio of P/L=0.24. The penetration and width of the weld pool are respectively P=1.6mm and

L=6.6mm with a ratio of P/L=0.24. The width of the thermally affected zone (ZAT) is in the order of 1.6mm Figure IV.3.These results are in line with those found by [6].

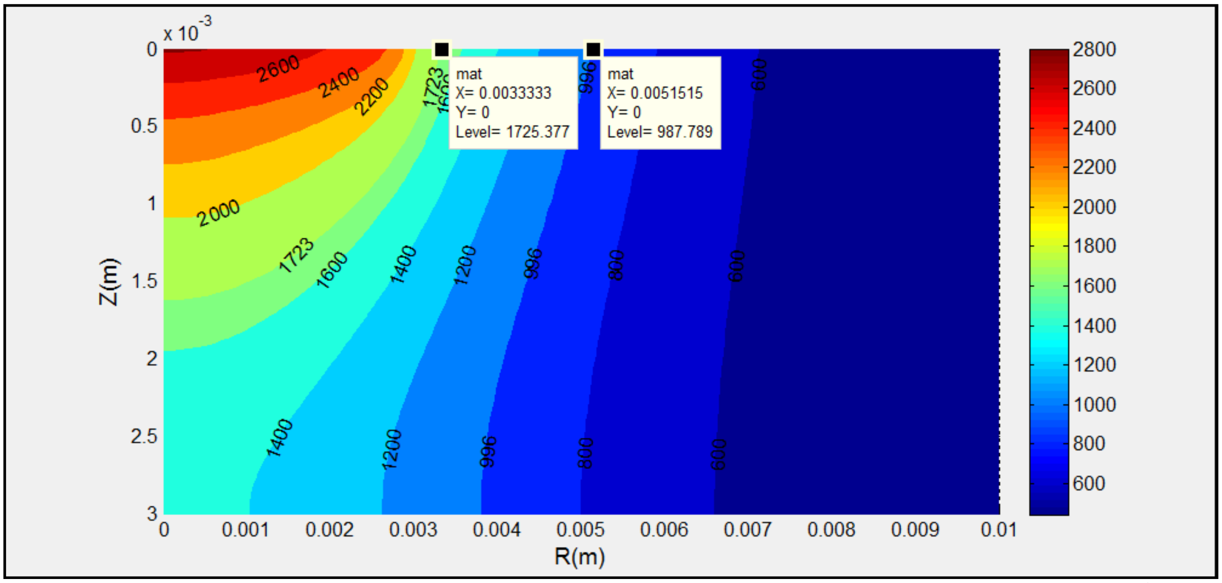

Figure IV.3 : Temperature distribution and isotherms calculated with conduction plus convection case $\frac{\partial\gamma}{\partial T} < 0$.

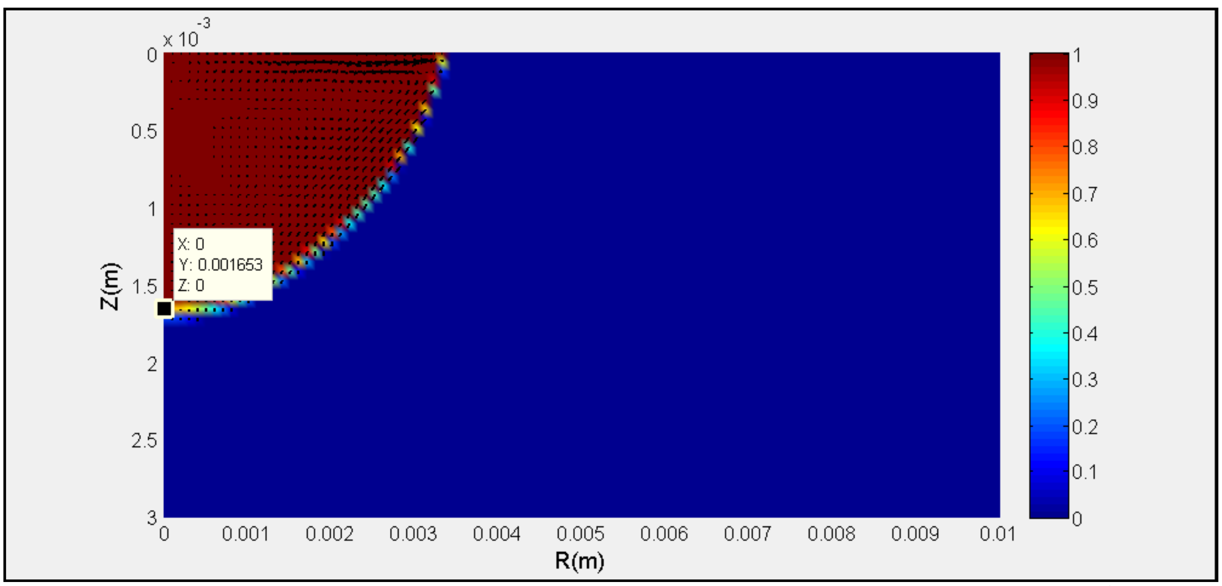

Figure IV.4 : Fluid fraction and field of calculated speed with conduction plus convection case $\frac{\partial\gamma}{\partial T} < 0$.

In the third case we have done the same previous calculations except this time with a positive surface tension gradient $\frac{\partial\gamma}{\partial T} < 0$. This case is obtained experimentally tensioactive elements are added during welding. The temperature distribution and calculated isotherms are represented by Figure IV.5. The maximum temperature is about 2000 K, this value is lower than the previous two cases. This decrease is due to the orientation of the flow to the weld pool surface that directs the energy delivered by the heat source inwards, which gives a centripetal brewing and increases the exchange surface by conduction. The maximum speed calculated in the order of 0.28 m/s. In the third case the penetration increases to have a depth of P=2mm Figure IV.6, the width of the weld pool is in the order of L=5.4mm with a ratio of P/L= 0.37. The width of the thermally affected zone (ZAT) is in the order of 3.3mm Figure IV.5.

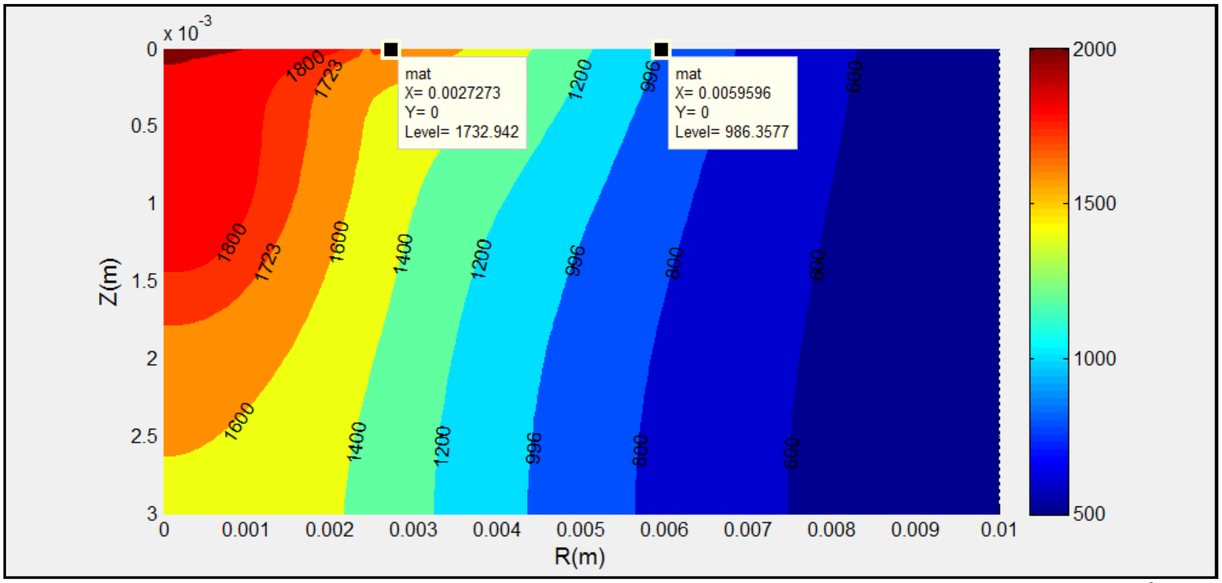

Figure IV.5 : Temperature distribution and isotherms calculated with conduction plus convection case $\frac{\partial \gamma}{\partial T} > 0$.

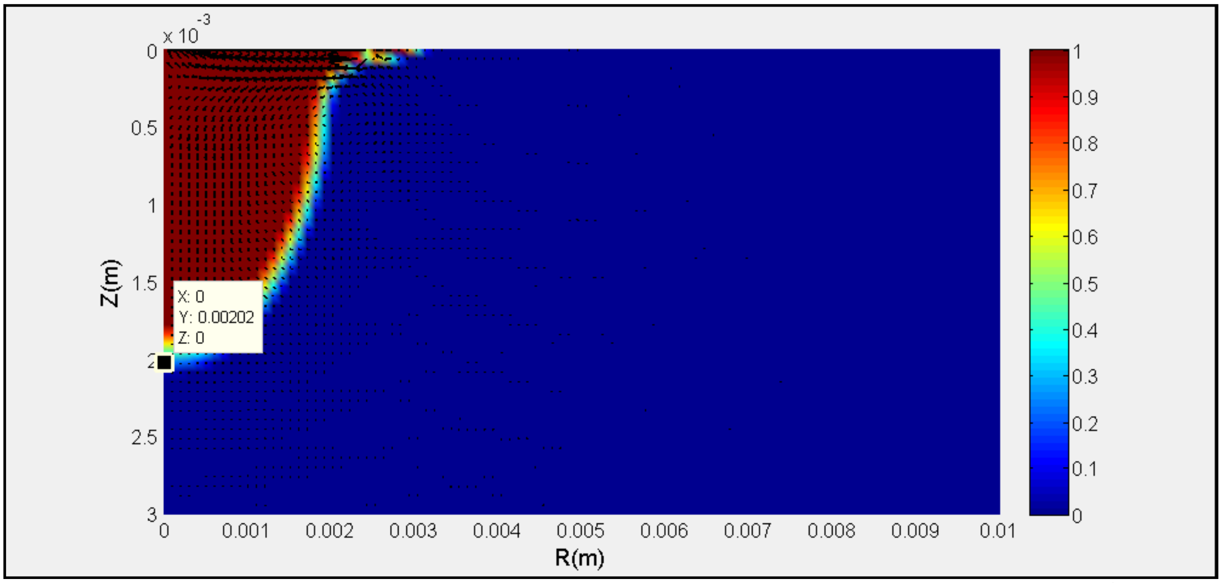

Figure IV.6 : Fluid fraction and field of calculated speed with conduction plus convection case $\frac{\partial \gamma}{\partial T} > 0$.

CONCLUSION

In this work a two-dimensional TIG welding model of a straight section of a 304L stainless steel sheet was developed. This model consists of coupling the heat equation with a diffusion equation from the stream equation with a convection- diffusion equation from the vorticity equation. In the first case we study that the thermal problem, only the mode of heat transfer by conduction was taken into account. The second case is to add the convection problem in our calculations to see the effect of the movement of the molten metal on the morphology and size of the weld pool when the surface tension gradient is negative. The third case was done the same study as the second case except for a positive surface tension gradient. The results of the calculations obtained for the distribution of temperature at the second t=2s show that there is a variation depending on the mode of transfer used, the maximum temperature increases in the second case compared to the first case, temperature decreases in the third case compared to the previous two cases. This is due to the sense of movement of the molten metal in the weld pool. The penetration calculated from the fraction of liquid shows an increase in the last two cases, especially when the surface tension gradient is positive. The width of the weld pool increases in the second case, i.e. when the surface tension gradient is negative. The expansion of the thermally affected zone (ZAT) calculated shows a decrease in the second case when the exchange area per conduction decreased compared to the first case; on the other hand, there is an increase in the third case compared to the previous two cases, as the exchange area per conduction has increased.

NOMENCLATURE

Cp	Specific heat capacity, 602J/(kg.K)
g	Gravity acceleration, 9.81m/s2
h	Convective heat exchange coefficient, 15 W/(m2K)
I	Welding current, 120 A
V	Welding arc voltage, 14 V
T_L	Liquidus temperature, 1723 K
T_S	Solidus temperature, 1673 K
k_L	Thermal conductivity of molten metal, 20 W/(m.K)
k_S	Thermal conductivity of solid metal, 24 W/(m.K)

Greek symbols

ρ_L	Density of molten metal, 6350Kg/m^3
ρ_S	Density of solid metal, 7500Kg/m3
η	Heat input efficiency, 0.7 %
μ_0	Magnetic permeability of vacuum, 1.26 10^{-6} H/m
σ	Stephan-Boltzman constant, 5.67$10^{-8}$Wm-2K-4
ε	Emissivity of body surface, 0.82
ΔH	Latent heat of fusion, 272 kJ/kg
β	Coefficient of thermal expansion, 10^{-4} 1/°K
$\partial\gamma/\partial T$	Surface tension gradient, -10^{-4} N/(m.K)

Subscripts

L	Refers to fluid
S	Refers to solid

REFERENCES

[1] T. Lant, D.L. Robinson, B. Spafford, J. Storesund, “Review of weld repair procedures for low alloy steels designed to minimise the risk of future cracking,” Int. J. Press. Vessels Pip.vol.78, pp. 813-818, 2001.

[2] W.Lucjan, “Failure analysis of the wing-fuselage connector of an agricultural aircraft,”Eng. Fail.Anal, vol.13.no. 4, pp. 572-581, 2006.

[3] Tsao, K. C. and Wu, C. S. (1988), “Fluid flow and heat transfer in GMA weld pools,” Weld. J., vol. 67, no. 3, p. 70s–75s.

[4] Aissani, M., Guessasma, S., Zitouni, A., Hamzaoui, R., Bassir, D. and Benkedda, Y. (2015), “Three-dimensional simulation of 304L steel TIG welding process: Contribution of the thermal flux,” Appl. Therm. Eng., vol. 89, pp. 822–832.

[5] Li, Y., Feng, Y., Li, Y., Zhang, X. and Wu, C. (2016), “Plasma arc and weld pool coupled modeling of transport phenomena in keyhole welding,” Int. J. Heat Mass Transf., vol. 92, pp. 628–638.

[6] Kim, W.-H., Fan, H. G. and Na, S.-J. (1997), “Effect of Various Driving Forces on Heat and Mass Transfer in Arc Welding,” Numer. Heat Transf. Part A Appl., vol. 32, no. 6, pp. 633–652.