JCARME
ISSN: 2228-7922
Journal of Computational and Applied Research in Mechanical Engineering
Vol. 7, No. 1, pp. 47-56
jcarme.srttu.edu

Investigation of fluid flow and heat transfer in aluminum tube hot gas forming process

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Article info:
Received: 12/04/2016
Accepted: 17/06/2017
Online: 13/08/2017

Keywords:
Hot metal gas forming,
Aluminum alloy tube,
Fluid flow,
Heat transfer,
Temperature distribution.

Abstract

In this study, hot metal gas forming of AA6063 aluminum tube is numerically studied with a focus on heat transfer of both fluid and solid phases. An experimental study is simultaneously conducted to validate the numerical results. Finite volume method has been used to discretize the governing equations. Pressure-velocity coupling of fluid phases are performed through the SIMPLEC algorithm. Some of the most important outputs of the present study are velocity distribution of fluid inside the tube as well as the fluid in the gap between tube and matrices. Because of non-homogeneous distribution of temperature on the tube surface, circulating flows are generated inside the tube which may have considerable effects on heat transfer. It is seen that after 400 s, number of the circulating flows doubles. Analysis of temperature distribution reveals that middle part of the tube reaches 500 ℃ after 600 s and other parts have higher temperature. By applying an efficient control method for heating, temperature distribution of the tube reaches a more homogeneous form.

Nomenclature

c_p	Specific heat, J/(kg.K)	***Greek Symbols***	
g	Gravitational acceleration, m/s^2	β	Volumetric thermal expansion coefficient, 1/K
k	Thermal conductivity, W/(m.K)	μ	Viscosity, kg/(s.m)
P	Pressure, Pa	ρ	Density, kg/m^3
q'''	Heat generation, W/m^3	***Subscripts***	
T	Temperature, K	b	Belt heater
t	Time, s	c	Cartridge
u	x-velocity, m/s	d	Die
v	y-velocity, m/s	f	Fluid
w	z-velocity, m/s	i	Inner
x	X coordinate, m	o	Outer
y	Y coordinate, m	ref	reference
z	Z coordinate, m	***Superscripts***	
R	Radius, m	$'''$	Per unit volume
D	Diameter, m		
L	Tube length, m		

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1. Introduction

Nowadays, automobile industries need lightweight parts to reduce weight of vehicles and thus fuel consumption. Aluminum alloys are acceptable choices, but, their weak formability in low temperatures leaves no way but high temperature forming methods. The hot metal gas forming (HMGF) is one of the most efficient forming methods in which the part is formed in lower pressure. In addition, metallurgical properties of the alloy are enhanced [1].

Several studies are conducted dealing with HMGF. Here, some of the relevant studies are presented. Vadillo et al. [2] studied HMGF of ferritic stainless steel tube numerically and experimentally. They implemented the finite element method to model the forming. They compared the tube deformation evaluated from the numerical and experimental studies, concluding that, neglecting the temperature gradient in the tube leads to inaccurate results. Different thermal heating conditions and input pressure curves were considered in their study. Kim et al. [3] used the HMGF method in forming of an Al-Mg-Cr alloy tube. First, temperature of the die was elevated to 793 K and the cold tube was kept in the die for 20 minutes. By closing both sides of tube, pressurized nitrogen gas was inserted in the tube. The pressure was kept in a range of 50 to 70 bars. The deformation was observed in 70 seconds after the gas supply, having no defects on the formed surface. Zoei et al. [4, 5] performed a FEM analysis of HMGF of AA3003 aluminum tube. In addition, they experimentally investigated the forming. The temperature was elevated to 600 ℃ by using heating elements. They concluded the HMGF is an efficient method in forming of aluminum alloys. The observed that higher temperature may improve the forming in lower gas pressures. In He et al. [6] study, a TA2 tube was formed by using HMGF. The tube temperature was elevated to 950 ℃ by using induction heating. A high frequency induction heater of 20 kW was used. The results revealed that shape of the induction coil plays an important role in forming. In an equal diameter coil, bulging of the tube was nonhomogeneous, while by using a variable diameter coil, the temperature gradient was nearly homogeneous. The deduced the optimum temperature of TA2 tube forming is in a range of 860 to 920℃. Maeno et al. [7] investigated bulging of an AA6063 aluminum tube by using resistance heating. They examined the effects of internal pressure and heater current density on the expansion ratio of the tube. Two copper electrodes were attached to ends of the tube and temperature of the tube was increased by passing the electrical current thorough its wall. Outer surface of the tube was covered by graphite to use the thermography in temperature measurements. The results showed that in a current density of 38 A/cm^2, defects are seen in internal pressures of 0.2, 0.4 and 0.6 MPa, while an acceptable forming was performed in an internal pressure of 0.8 MPa. An expansion ratio of 132 % relative to cold forming was reported in their study. They proposed using low conductivity die to ensure desirable forming of the tube corners. In another study, Maeno et al. [8] used the HMGF method in forming a hollow part of ultrahigh strength steel by implementing a resistance heating. Nasrollahzade et al. [9] experimentally studied the HMGF of an AA6063 aluminum tube of 40 mm and 1.5 mm, in diameter and thickness, respectively. Sharp corner dies were produced of SpK (Special K) by machining. Cartridge heaters of power 800 W and a belt ceramic heater of power 2000 W were used to increase the tube temperature from cold state to 400-500 ℃. High-pressure nitrogen was supplied from a storage capsule when the tube temperature was in desirable value. They reported that by increasing the tube temperature from 400 to 500 ℃, better corner filling was observed. Wang et al. [10] experimentally studied HMGF of a laser-welded TA15 titanium alloy tubes. The tube temperature was increased to 650-750 ℃ by using an induction heater. Paul and Strano [11] performed a study by designing an experimental setup capable of cooling and heating. The tube temperature was kept in a range of 950-1150 ℃ and the gas pressure was in a range of 30-60 MPa, resulting in a forming time of 1 to 4 seconds. Dong et al. [12] studied hot forming of AA6082 using plasma introducing new methods of heating which may improve the temperature distribution.

In the present study, heat transfer of both fluid and solid phases are numerically examined in a hot metal gas forming of an aluminum tube. Governing equations of fluid phases, consisting of the continuity, momentum and energy equations are solved with energy equations of solid phases. To validate the numerical results, an experimental setup is constructed, measuring the tube middle temperature in specific times. To the best of our knowledge, it is the first paper in HMGF in which the effects of the fluid phases are fully considered on the process and especially tube temperature distribution. In addition, since the present study is performed in a transient form, valuable data may be achieved in different times from the beginning.

2. Mathematical formulation

Schematic view of the problem including tube, die, cartridge heaters and ceramic belt heater is illustrated in Fig. 1. A circular aluminum tube is placed inside the die to be formed as square shaped. Only one half of the problem is solved since the problem is symmetrical relative to the x-axis. Two fluid phases are present in this problem, one inside the tube which is supplied from pressurized nitrogen capsule and air which is trapped between the tube and the die. It is assumed the gases are ideal gases satisfying the Boussinesq approximation, which is given in Eq. (1) [13]. All the phases consisting solids and fluids are at room temperature at first and there is no leakage. It should be mentioned that in real forming process, leakage is possible but to simplify the numerical study, it is neglected. In this study, the phenomenon before forming is studied and the tube is circular at all the analysis time.

By using the Cartesian coordinates, differential governing equations consisting of the continuity, momentum and energy equations are given as Eqs. (2)-(4) for the fluid phases. Heat conduction in solid phases are governed by using Eq. (4) either. It should be mentioned that thermophysical properties of each phase should be used in applying the following equations [13].

$$\rho = \rho_0 \left[1 - \beta \left(T - T_{ref} \right) \right] \tag{1}$$

$$\frac{\partial \rho_f}{\partial t} + \frac{\partial \left(\rho_f U_i \right)}{\partial x_j} = 0 \tag{2}$$

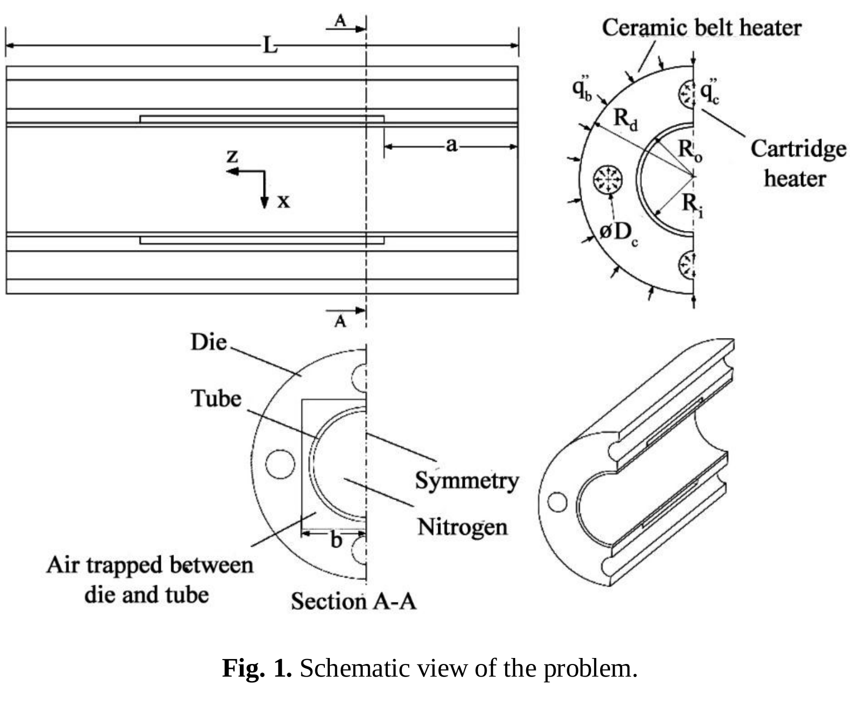

Fig. 1. Schematic view of the problem.

$$\frac{\partial(\rho_f U_i)}{\partial t}+\frac{\partial(\rho_f U_i U_j)}{\partial x_j}= -\frac{\partial P}{\partial x_i}-\rho_f g_i\left(T-T_{ref}\right)+\mu_f\frac{\partial^2 U_i}{\partial x_j \partial x_j} \quad (3)$$

$$\frac{\partial(\rho T)}{\partial t}+A\frac{\partial(\rho U_j T)}{\partial x_j}=\left(\frac{k}{c_p}\right)\left(\frac{\partial^2 T}{\partial x_j \partial x_j}\right); \quad \begin{cases} A=1 & for\ fluids\ phases \\ A=0 & for\ solid\ phases \end{cases} \quad (4)$$

No slip velocity boundary conditions are applied at the inside wall of the tube as well as the walls of the gap between the tube and the die. Constant heat fluxes are imposed to the interfaces between the heaters and the die. Coupled thermal boundary conditions are implemented in contact surfaces of the phases. Side walls of the die and the sealants of the tube are in contact with the surrounding room air.

3. Numerical method

In the present study, a numerical model was implemented to solve the 3D conjugate heat transfer in the HMGF, accounting for free convection inside the tube and the gap between the tube and matrices as well as the conduction in the matrices and tube wall by Ansys® Fluent®. Finite volume method has been used to discretize the governing equations. Pressure-velocity coupling of fluid phases are performed through the SIMPLEC algorithm of Van Doormal and Raithby [14]. Convective and conductive terms were discretized using first order upwind and second order central difference schemes, respectively. A time step of 0.02 s is implemented to ensure convergence. As the solution is transient, each time step is repeated 60 loops with a residual of 10^{-6}. The grid was generated using Gambit software. It was observed that by choosing 406560 computational cells, the solution was independent of the mesh and there was no need for finer grid.

4. Experimental setup

To validate the numerical part, an experimental setup is constructed as shown in Fig. 2(a). As illustrated in Fig. 2(b) an AA6063 aluminum tube with outer diameter of 40 mm and thickness of 1.5 mm is used which is made by extrusion process. A die made of stainless steel 304 (Fig. 2(c)) is used having two cone shaped parts to seal both sides of the tube. Since the sealants slope is small, the sealants are in good contact with the tube and there exists an acceptable contact area which ensures the sealing. On the other hand, the sealant material is selected as the die to have the same thermal expansion coefficient. In addition, after starting the forming, the screws behind the sealants are fastened again to lessen the leakage. Therefore, the leakage is not considerable in the experiments. Two types of heating elements are implemented in this study, four cartridge heaters each with a power of 300 W and a ceramic belt heater with a power of 2200 W. The heaters, die and tube are shown in Fig. 2(d). A type K thermocouple is placed in the middle section of the tube surface as shown in Fig. 2(e). Silicon paste is used to reduce the contact thermal resistance between the thermocouple and the tube surface. A cylindrical insulation is place around the thermocouple, ensuring that the tube temperature only influences the thermocouple. Tube temperature and pressure of the fluid inside the tube are two important parameters of the HMGF process [15]. In the experimental study, several cases are defined to find the appropriate range of pressure and temperature of forming. The unsuccessful forming attempts are illustrated in Fig. 2(f). Finally, it is concluded that applying the internal pressure from the beginning leads to better corner filling. The tube temperature is elevated to 500 ℃ to enhance the superplastic forming. An internal pressure of 8 bar is applied from the beginning. After 40 minutes, a pressure drop of 5 bar is observed as a result of forming. As shown in Fig. 2(g), a fully symmetrical part without any burst is produced. The above-mentioned parameters are then used in the numerical part.

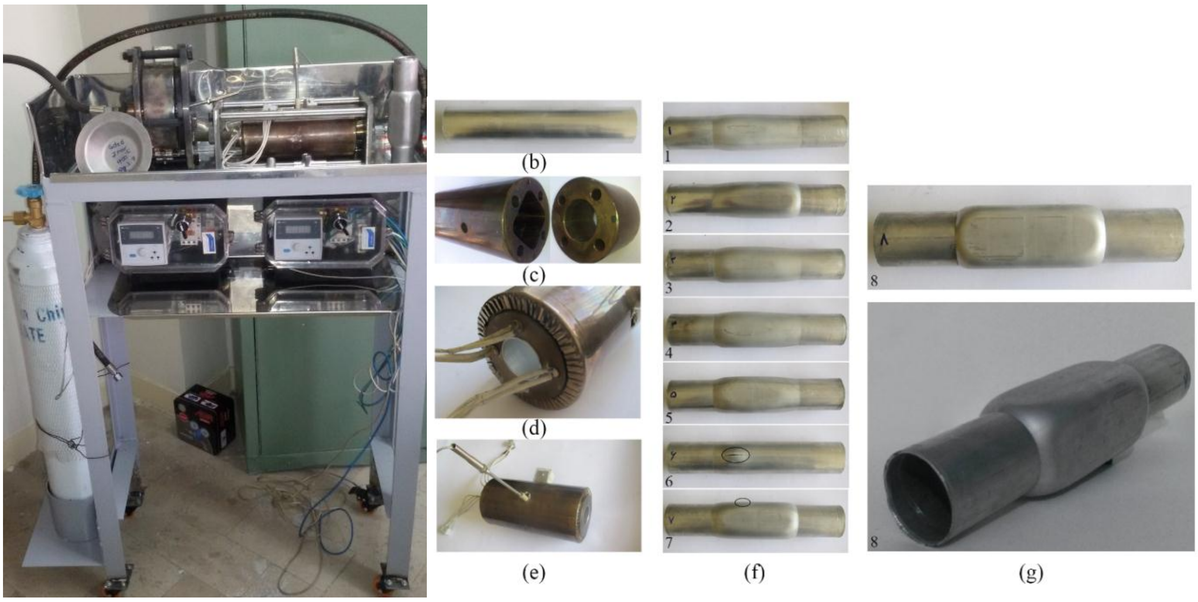

Fig. 2. Experimental setup (a) constructed setup (b) unformed tube (c) die (d) die and heaters (e) temperature sensor location (f) unsuccessful forming attempts (g) satisfactory forming.

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5. Results and discussion

In this section, first, numerical results are validated by using data extracted from experimental study. Then, results of present study consisting velocity and temperature field of fluid inside tube and gap, as well as the temperature distribution of tube are presented.

5.1. Validation of numerical results

In Fig. 3, variation of temperature of middle part of the tube surface is illustrated for both numerical and experimental studies before the forming. It is seen the numerical results are in good agreement with experimental data showing acceptable accuracy of the present study.

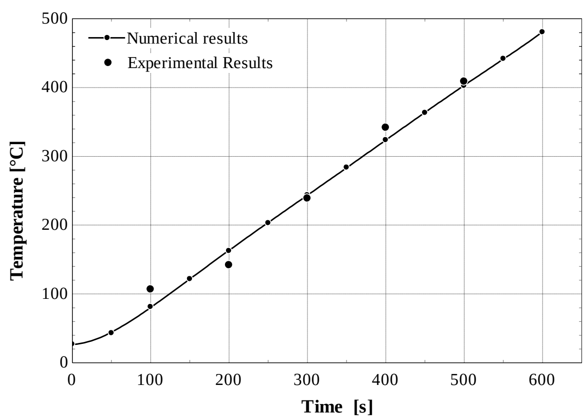

Fig. 3. Validation of numerical study with experimental results.

5.2. Velocity and temperature fields of fluid phases

Fluid phases are referred to the fluid inside the tube (N_2) and the fluid trapped between the tube and die (air). In Fig. 4(a), z-velocity contours of N_2 are presented in two z-planes in various times after process beginning. According to direction of flow in sections, it is concluded that circulating flows are present in the tube, one clockwise and the other counterclockwise. By time passing, the magnitude of the velocity is decreased. Fig. 4(b), presents streamlines of flow in different times showing the circulating flows in a much sensible manner. As shown in this figure, in 400 seconds after the beginning, number of circulating flows have been doubled, because more heat is given to the nitrogen in the sections where the tube is in contact with the die. Therefore, there exists considerable driving force to circulate the fluid.

In Fig. 5(a), temperature contour of N_2 in multiple sections of the tube are presented showing less values in z=0 because of fluid trapped in gap. On both sides of the gap, the tube is in contact with die and the heat is conducted through the connection, while in gap, heat is transferred by free convection only. This may lead to deficiencies in tube temperature, which is considered in next section. Temperature of N_2 rises through time and this is the reason of why the z-velocity lessens by time. In Fig. 5(b), temperature contours of the air trapped between the tube and die are illustrated. It is seen that air temperature is lower at z=0, because it is far from the tube-die contact area.

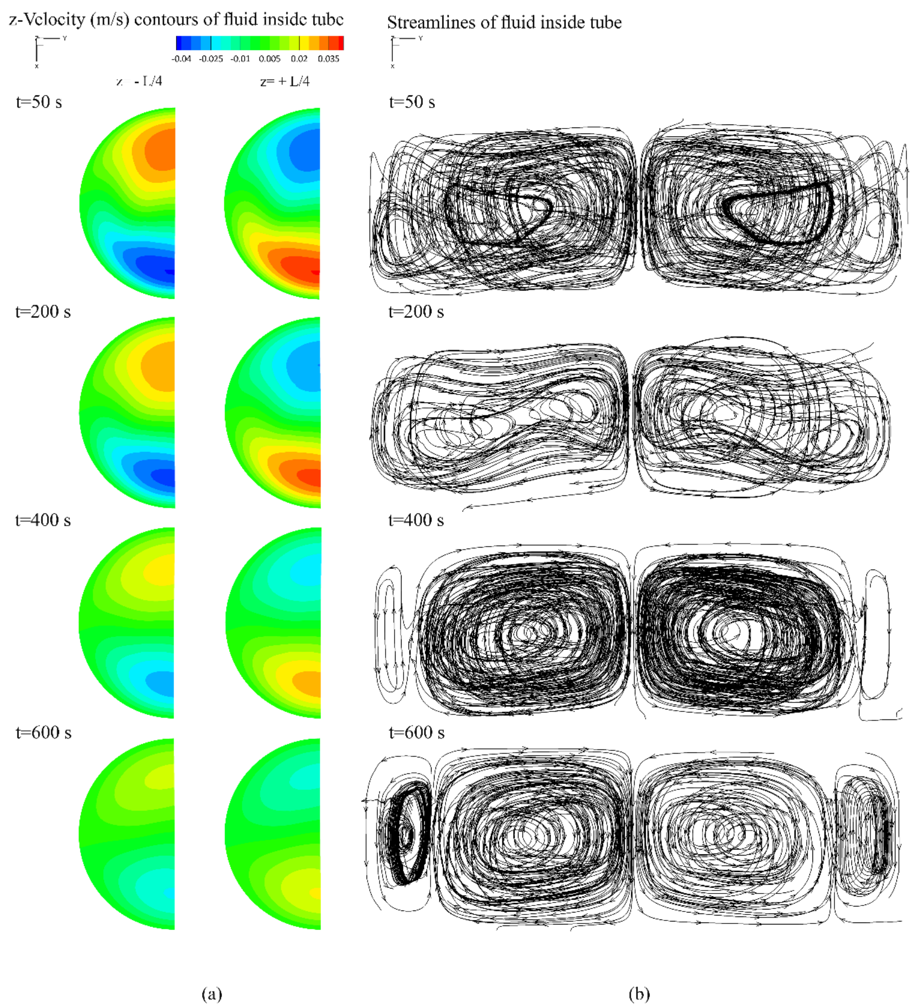

Fig. 4. (a) Contours of z-velocity at various z-planes (b) streamline of fluid inside the tube, at different times from the beginning.

5.3. Temperature distribution of the tube

In Fig. 6, contours of the tube temperature are illustrated in different times from process beginning. It is seen the middle section of the tube has lower temperature that is because of the fluid inside the gap. A temperature difference of 10℃ is observed in all cases which reveals the importance of finding a method to handle nonhomogeneous distribution of temperature in tube surface. The heating is stopped in t=600 s and the heaters are off for 200 s. Since aluminum has high thermal conductivity, this gives a time to the heat to be conducted through the tube walls into the middle part. Then, the heaters are turned on for 50 s and turned off again as shown in Fig. 7.

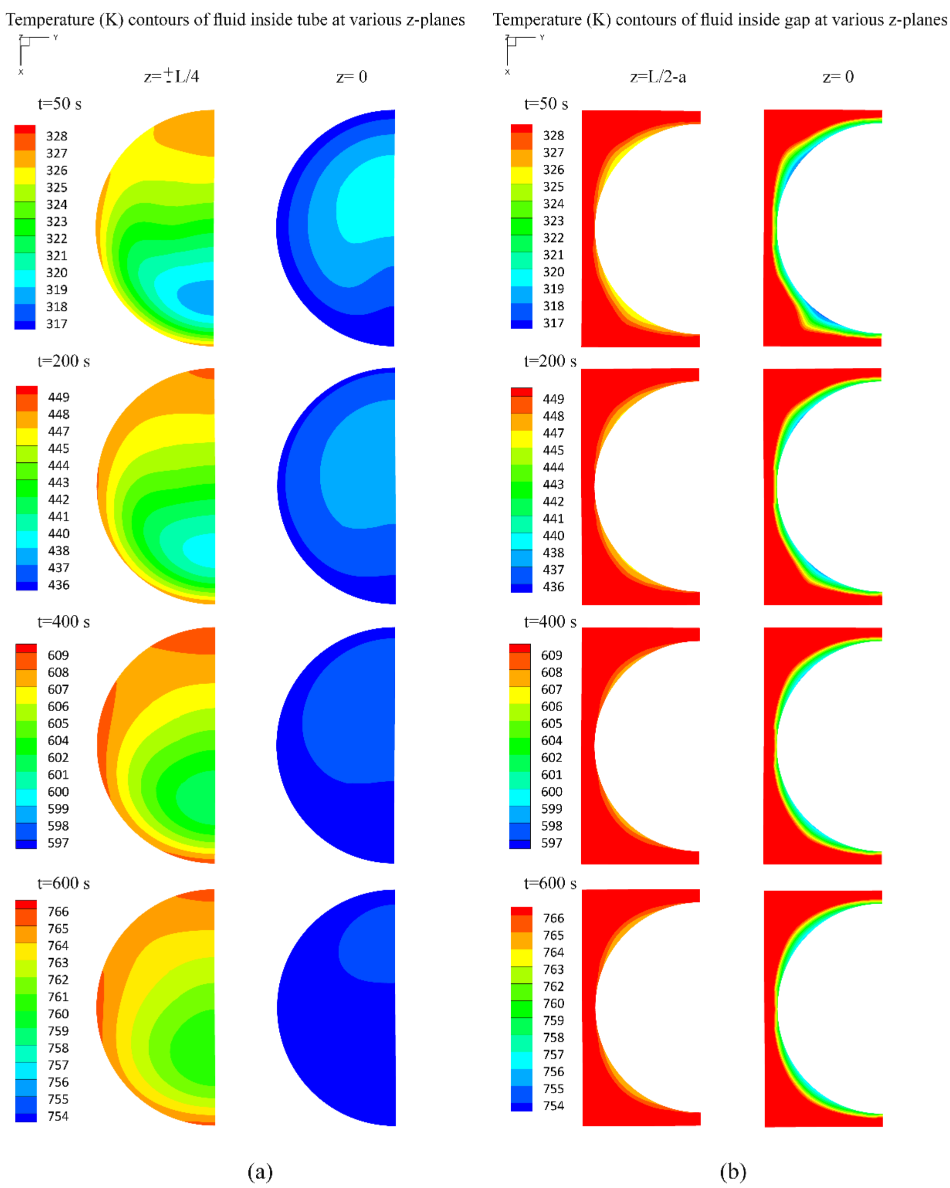

Fig. 5. Temperature Contours (a) fluid inside the tube (b) fluid trapped between the tube and die at various z-planes and different times from the beginning.

Temperature contour of the tube in t=1000 s is illustrated in Fig.8. It is obvious by using heater power control procedure more homogeneous temperature distribution is achieved in tube, which is a necessary requirement for a successful forming.

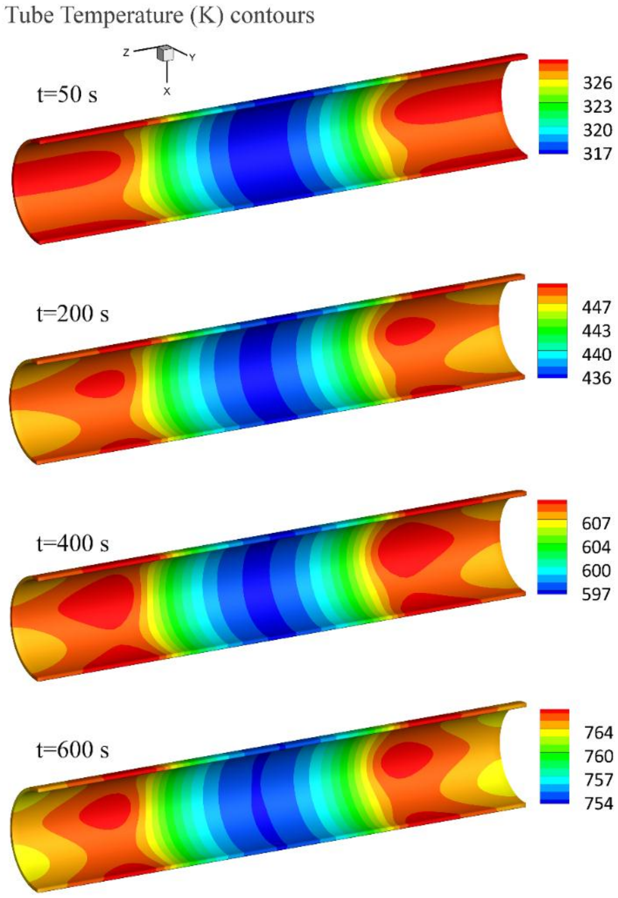

Fig. 6. Temperature contours of the tube surface.

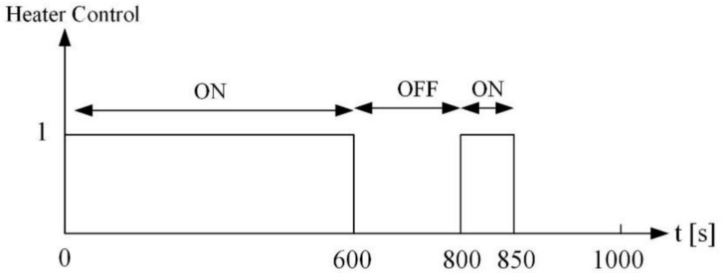

Fig. 7. Control method of heaters power.

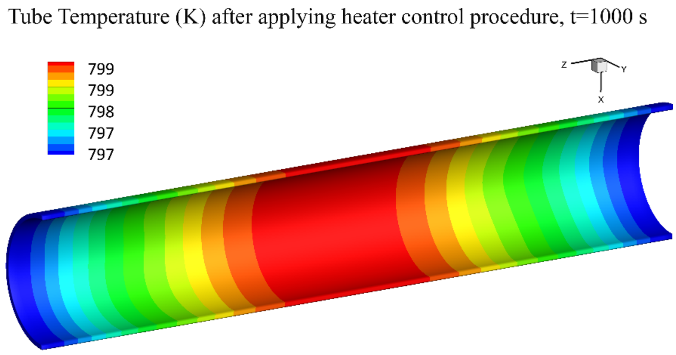

Fig. 8. Contour of tube temperature at t=1000 s by applying the heater power control method.

6. Conclusions

In this study, transient 3D conjugate heat transfer in HMGF of aluminum tube was investigated considering both convection in fluid phases and conduction in solid phases.

- According to presence of high-pressure gas inside the tube, present study may be a new approach in this filed because no similar study exists in the literature considering free convection of the fluid phases in HMGF.
- Comparison of the results with the results of the experimental setup showed the accuracy of the model.
- The results showed that circulating flows are present inside the tube and the gap which may have considerable effects on the temperature distribution of the tube.
- The circulating flows double after 400 seconds of heating.
- By turning the heaters on and off, a homogeneous temperature distribution was achieved.
- The heating control algorithm, reduced the tube temperature difference from 10 ºC to 2 ºC.

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How to cite this paper:

J. Shahbazi Karami, and GH. Payganeh, " Investigation of fluid flow and heat transfer in aluminum tube hot gas forming process", Journal of Computational and Applied Research in Mechanical Engineering, Vol. 7. No. 1, pp. 47-56

DOI: 10.22061/JCARME.2017.647
URL: http://jcarme.srttu.edu/article_647.html