Simulation of die heating for forgings and pressure castings by convective heating systems

MHI Aritcle # 4 (Further information including Airtorch Catalogs may be obtained by contacting MHI at 513-772-0404 or 513-672-3333 (fax) or by email at Airtorch™@mhi-inc.com.)

Abstract

A comparison is made of die temperature uniformity for different heating configurations. The two situations which are compared are an electric air heater and flame heating. The temperature uniformity with electric air heating is noted to be substantially superior to flame heating of large dies. The simulation results are compared with experimentally obtained numbers and found to be in agreement.

Introduction

The heating of the die is often the most critical start up procedure in forging, extrusion and pressure die casting operations. Improper pre-heating results in a variety of problems, the most significant being low die life on account of non-uniform temperature along the surface of the die (the primary cause for early failure or distortion from thermal fatigue).

A wide variety of thermal processing techniques are used for die heating. Most commonly, the dies are heated with one or several gas flame torches. Often, the gas torches are arranged in a manner so as to produce a distributed heat source on the die surface. The common problems encountered with this heating method are carbon deposits, high noise, very significant temperature non-uniformities and a large temperature difference between the upper and lower die surfaces in vertical configurations. An alternative to die heating by flames torches, is available with a new device called the Airtorch™ which is a patented method of electrically heating air or gasses (1, 2). With the Airtorch™, the problems such as carbon deposits, noise and explosion hazard conditions are clearly avoided. In this article, we test for the temperature distribution and uniformity with such a system and compare the uniformity against flame heating. The use of a similar electrical device has been shown in previous articles to greatly diminish the power required in low and medium temperature ovens, enhance the uniformity in oven treated parts, and also completely eliminate distortion during the heat treating of complex castings (3, 4). Figure 1(a) shows a photograph of a 3kW, 10kW and 20kW Airtorch™ models.

Figure 1(a): Pictures of a 3, 10 and 20kW Airtorch™ models (counter-clockwise top to bottom). Picture reproduced with permission from Micropyretics Heaters International.

In this article, die heating by Airtorch™ is simulated by comprehensive computational fluid dynamic approach and predicted temperatures are compared with experiments. The air-flow pattern and, in turn, die heating are analyzed. The flame heating is simulated based on a simplified mathematical assumption model and compared somewhat with experimental data. Heating patterns of die by air-torch and flame are compared and reported.

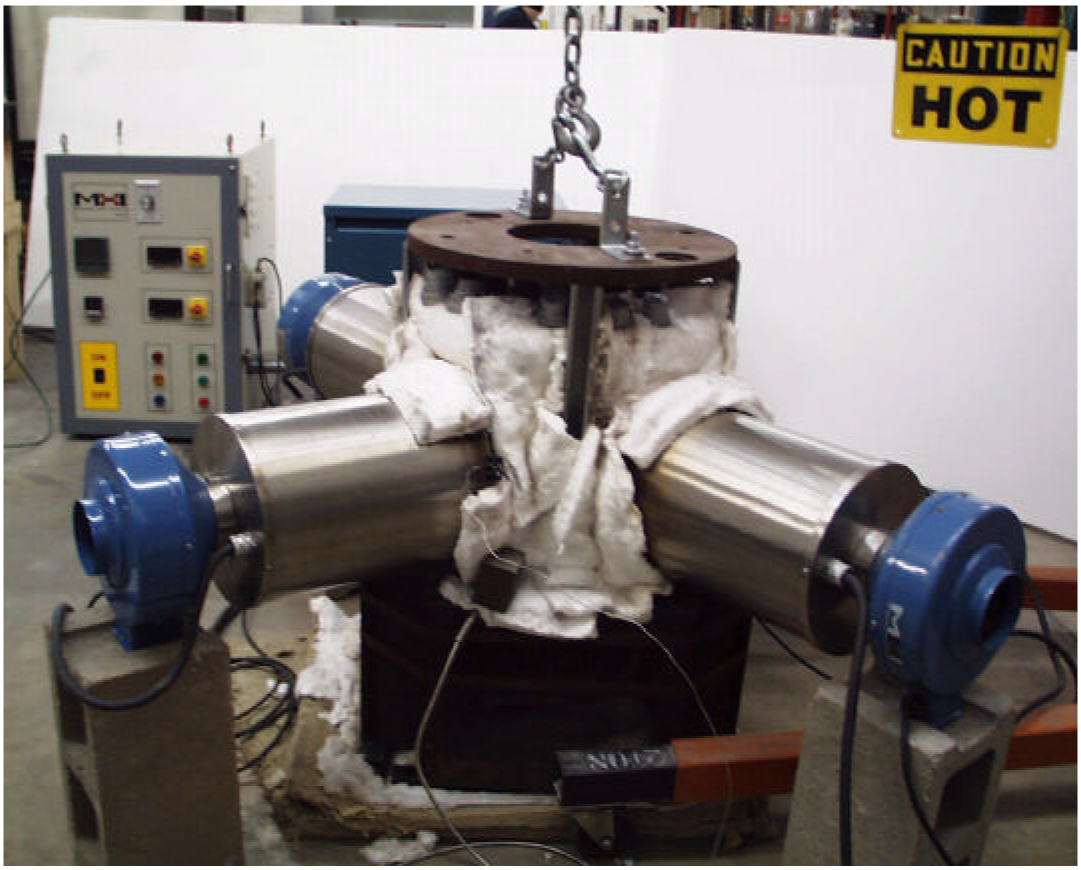


Figure 1(b) A typical configuration for die heating of an aluminum wheel die.

Numerical Simulation of Die Heating

Standard numerical techniques are used to simulate both the cases of die heating by flame and Airtorch™ heating. Experimental verification of the simulation results by comparing the temperature and heating rates obtained in complex dies (such as those shown in Figure 1(b)) is also attempted. The available dies are extremely complex and so are not simulated exactly except for their overall size and weight. The configuration considered is the horizontally opposed flat platen assembly commonly used for low pressure die casting.

A. Modeling of Die Heating by Airtorch™

Two dies of approximately 7500lbs are placed one above the other separated by a distance of 317.5mm. The dies are provided a heat insulation blanket made of Alumina-Silicate sheet 1” thick. The heat insulation blanket is held vertically from the top to the bottom die. The distance between the dies and the heat insulation blanket is 5mm. Hot air at 25 CFM and 1200°C is directed between the two dies by three Airtorch™ placed 120 degrees apart (Figure 1 (b)). The typical diameter of the Airtorch™ is approximately 254mm. In the present case, the air outlet is provided only close to the the top die through a narrow passage whereas there is no air outlet at the bottom die.

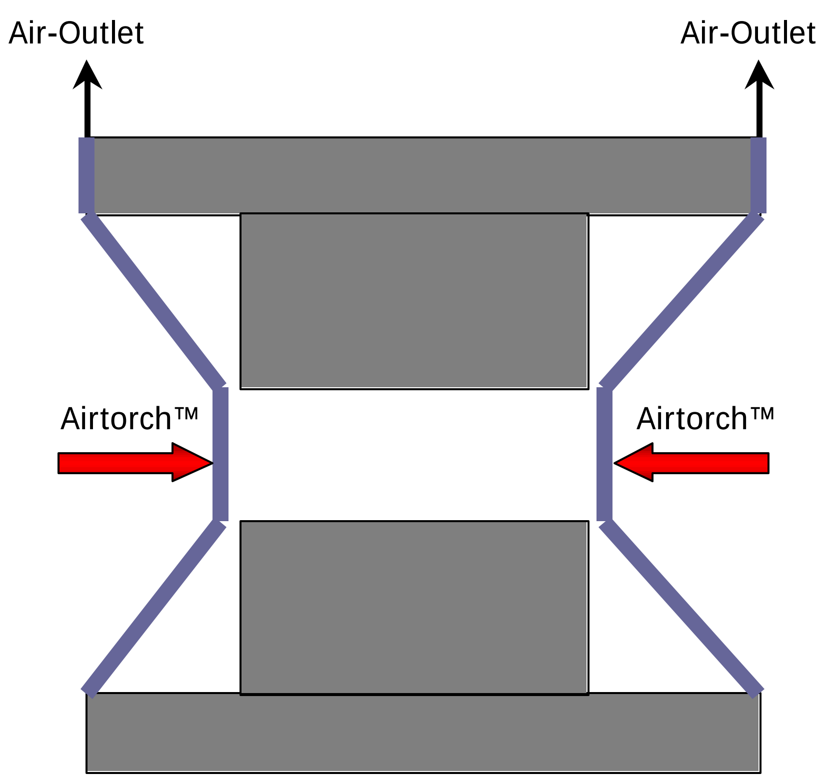


Figure 2: Schematic of die heating by Airtorch™

Die heating by the Airtorch™ is controlled by the thermo-fluid transport in the surrounding air and by thermal diffusion in the die. The heating of the die by Airtorch™ is governed by 1) the three dimensional Navier-Stokes equations in terms of conservation of mass, momentum and energy in the space between the two die and 2) three dimensional conservation equation of energy in the die. A detailed mathematical representation of the model is presented in the Table I.

Table I

The Model for Heating by Airtorch™

A general conservation equation for all transport variables in a Cartesian coordinate system is given by:

$$C_\Phi\left[\frac{\partial(r\Phi)}{\partial t}+\frac{\partial}{\partial x_i}(ru_i\Phi)\right]-\frac{\partial}{\partial x_i}\left(\Gamma_\Phi\frac{\partial\Phi}{\partial x_i}\right)=S_\Phi \qquad (1)$$

where Φ denotes a general transport variable such as energy, x_i the i-th Cartesian coordinate, u_i the i-th Cartesian velocity component, T the temperature of the fluid, r the density of the fluid, Γ_Φ the diffusivity of Φ (dynamic viscosity m or thermal conductivity l), and S_Φ the source term of Φ (such as heat generation per unit time). **Table II** gives the values of Φ, C_Φ, Γ_Φ and S_Φ for all transport equations applied in the model. Here, C_p denotes the specific heat at constant pressure. For simplicity, all equations are given in Cartesian coordinates. However, the computations were performed on curvilinear boundary-fitted grids.

The boundary conditions:

At the air inlet in three locations 120 degrees apart,

$V_{in(absolute)}$= 25 CFM and T_{in}=1200 C (2)

At the heat blanket surface,

Q = 0 and U=V=W= 0 (no-slip boundary conditions) (3)

At the Air outlet, an outflow boundary condition is specified,

$$\frac{d}{dx_i}\left(\frac{dv_n}{dx_i}\right)=0 \qquad (4)$$

Table: II

Transport Variable Φ, diffusivity Γ_{Φ} and source term S_{Φ} for the mass, momentum and energy equation

Conservation Variable	Φ	C_{Φ}	Γ_{Φ}	S_{Φ}
Mass	1	1	0	0
Momentum (j -th component)	u_j	1	m	$-\frac{\partial P}{\partial x_j}$
Energy	T	C_p	l	$m\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$

Numerical Details

The numerical solution of the governing equations is based on fully conservative finite volume discretization on non-orthogonal boundary-fitted grids with non-staggered arrangement of variables. Block structured grids where the grids are globally unstructured and locally structured, are used and 33507 control volumes are generated in 33 blocks to discretize the computational domain. Using fully implicit time marching, the governing equations are solved. Small time-step (1s) is used untill the flow field reached a quasi-steady state and large time-step (20s) is used beyond time. The simulations are performed using FASTEST-3D which is a high-performance block-structured CFD code [6]. Different steps to perform the simulation and optimization of heating of the die are outlined in the Table III.

Table III

Steps to optimize die heating by Airtorch™

1. Geometric modeling of die assembly.
2. Multi-block grid generation for complete assembly.
3. Applying boundary conditions to solution domain.
4. Specifying Process parameters and Material properties.
5. Specifying Numerical parameters.
6. Numerical Simulation
7. Post processing of results

B. Modeling of Die Heating by Flame

Multiple oxy-acetylene flames at different locations are used in this heating system. Flame to die heat transfer is extremely complicated involving radiation, convection and diffusion of flame. A simplified approach is followed in this article to model the flame heating as outlined below.

In order to model the thermal transport in the die, a symmetric two-dimensional plane of the die is considered with flame heating in the corner as shown in Figure 2. The flame is directly in touch with the surface of the die and the die surface under the flame (i.e., S_{flame} as shown in the Figure 3) depends on the diameter of the flame, distance of the torch from the surface as well as the fuel flow rate. The flame heating is modeled by radiative heat transfer from the flame to the die surface under the flame (S_{flame}). Although the adiabatic temperature of oxy-acetylene flame is 3300°C, there are significant losses from the flame to ambient and the flame temperature, T_{flame}, is considerably lower than 3300°C. In the modeling approach as describe above, S_{flame} and T_{flame} are unknown and these are determined using experimental data of die temperature. The mathematical model of the flame heating is presented in Table IV.

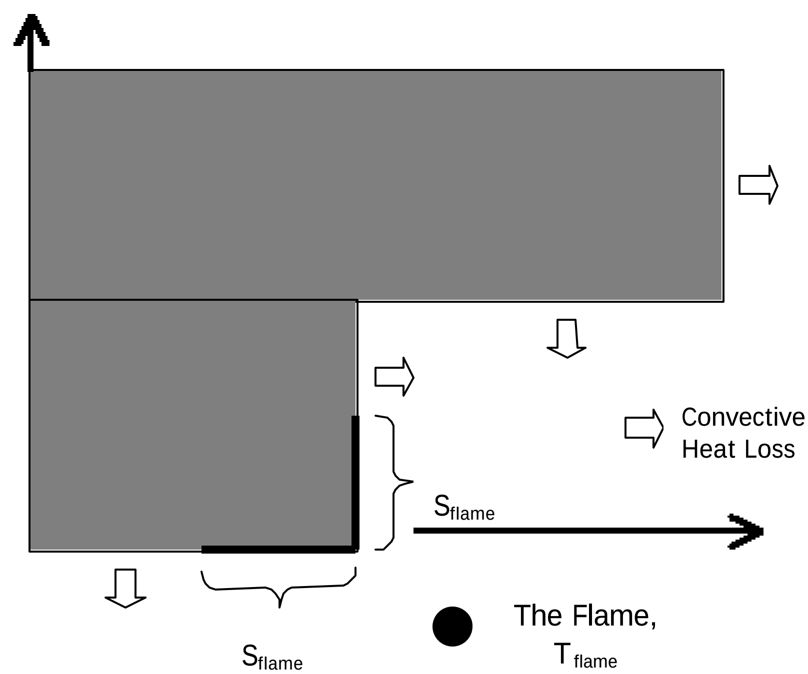


Figure 3: Modeling of Die Heating by Flame

Table IV

The Model for Flame Heating

The governing equation is due to conservation of energy as outlined below:

$$\frac{dT}{dt} - \alpha \nabla^2 T = 0 \tag{5}$$

Boundary Conditions

Along S_{flame} on the die surface, as shown in the Figure 2, radiative heat flux is imposed,

$$\frac{Q}{A} - \sigma\varepsilon \left(T^4{}_{flame} - T^4{}_{side}\right) = 0 \tag{6}$$

From the surface of the die exposed to the ambient, convective heat loss is In places where heat loss is considered,

$$\frac{Q}{A} - h \left(T_{side} - T_{ambient}\right) = 0 \tag{7}$$

Along the axis of symmetry, Q = 0

The convective heat transfer co-efficient is estimated using standard correlation [5]

1. For Vertical Flat Surfaces

$Nu = \{ 0.825 + (0.387\ Ra^{1/6}) / [1+(0.492/Pr)^{9/16}]^{8/27}\}$

2. For Horizontal flat Surfaces

$Nu = 0.27\ Ra^{1/4}$

Where Nu, Pr and Ra are Nusselt, Prandtl and Raleigh numbers respectively.

Based on these correlation's, $h_{vertical}$ and $h_{horizontal}$ are estimated to be 8.75 and 3.10 W/m^2 K respectively.

Numerical Details and Fine Tuning:

Using 7500 control volumes, the conservative finite volume equations are solved by fully implicit time marching and a time-step of 1 second is used for the simulation.

The die temperature near the top surface at 3 mm (approx.) from the top was measured to be 230°C after 75 minutes of flame heating. Using this data and the materials properties as presented in Table V, T_{flame} and S_{flame} are determined to be 1600°C and 6.5 cm respectively and to have a reasonable match between the measurement and predictions as shown in figure 4. Using these values of T_{flame} and S_{flame}, die heating by oxy-acetelene flame is further simulated in this article.

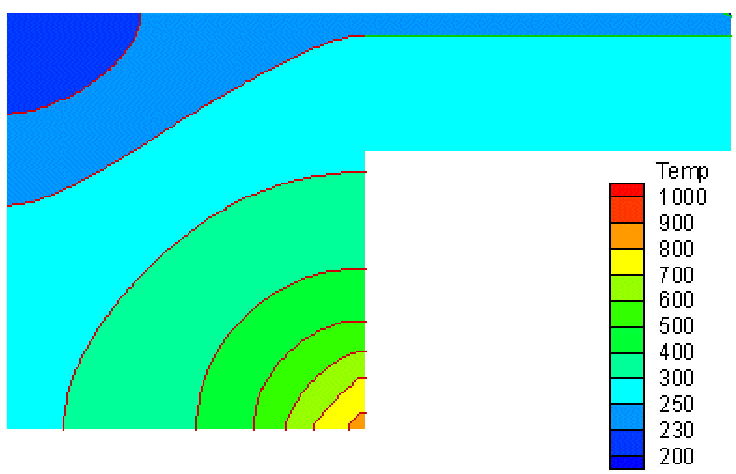


Figure 4. Predicted thermal field in the die after 75 minutes of flame heating

Table V

Material Properties of the Die [4] and Air [5] used in the simulation

Property	Die	Air
Density	7600 Kg/m^3	0.3166 Kg/m^3
Specific Heat	445 J/kg/K	1159 J/kg/K
Viscosity		449×10^{-7} Kg/m/s
Heat Conductivity	60 W/m^2 K	71.5×10^{-3} W/m^2 K
Emmisivity	0.3	

Results and Discussions

In actual die heating practice, the Airtorch™ is placed at an angle to the horizontal plane depending upon the air-outlet location and the die geometry. In the present study, the Airtorch™ placement is considered to be without any inclination in order to simplify the problem. Figure 4 presents isotherms and velocity field in the die-torch assembly at two cross-sectional planes (X-X' and Y-Y') after two hours of heating as shown in Figure 3. From the vector plot, a weak flow field can be noted around the sides of the bottom-die at both the cross-sections. Due to the zero inclination condition of the Airtorch™, the planar flow field from each Airtorch™ interacts and moves upward towards the outlet as can be noted in Figure 4. This results in an artificial theoretically low rate of heating in the lower die. Hence, the thermal field and heating pattern of the top die is considered for comparison with practical experience as well as for comparing with the simulated flame heating. Due to the strong flow and mixing, the thermal field around the top die is noted to be between 600°C and 800°C in the gas and provides a uniform heating environment.

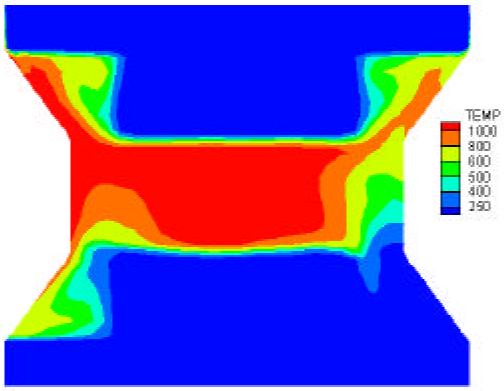
During heating of a typical medium sized forging die by the Airtorch™ assembly, the measurements of die temperatures were carried out at different time intervals; typical values are presented in Table 3. Figures 5 to 7 show the thermal fields in the die at 30 min., 1 hr 30 min. and 2 hrs through the isotherm plot. It is important to note that a representative die geometry (flat opposing horizontal configuration) is considered instead of the actual one for the sake of simplicity in the calculations. From Figures 5 to 7 and table VI, it is clearly noted that there is reasonable overall agreement between the predicted numbers and the measurement. Given the the approximation of the actual die geometry and Airtorch™, the placement at zero degree inclination, and the overall agreement in the thermal field clearly establishes validity of the simulation methodology for such heating.

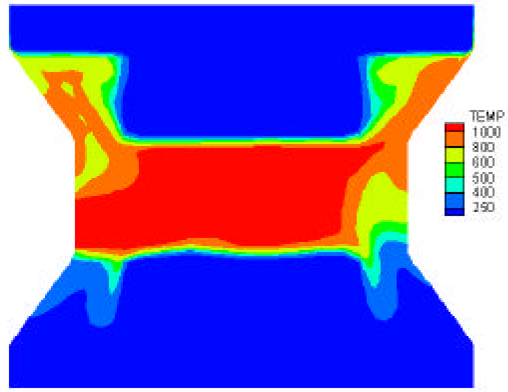
Table VI

Measured temperature of a die weighing 7500 lbs using three Airtorches™ each with 20 kW power

Time		Temperature, C
Hrs	Min.	
0	22	135
1	35	200
2	0	220

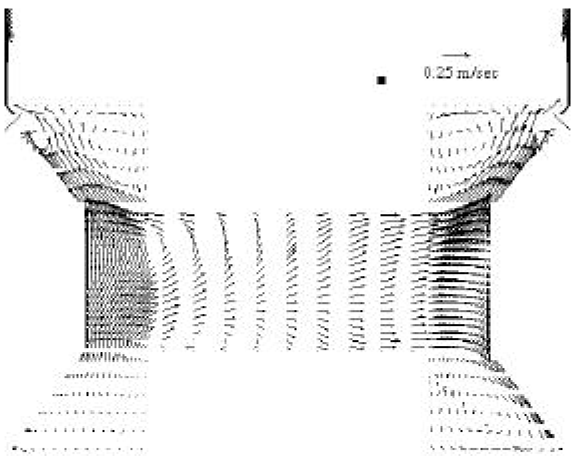
It is important to note from figures 4-6 that although the maximum thermal gradients are noted to be between temperatures of 135°C, 200°C and 220°C at 30 min., 1 hr 30 min, and 2 hrs respectively, most of the die surface has a thermal distribution with a very low temperature gradient. As discussed earlier, the flow field ensures a uniform heating environment (typically the temperature varies between 600°C and 800°C) during the entire period of heating; it was noted that the flow field reaches a pseudo steady state in a very short period from the beginning of the operation and ensures uniform heating for most the entire period. Such low thermal gradient during the entire heating period helps to reduce thermal distortion of the die significantly.

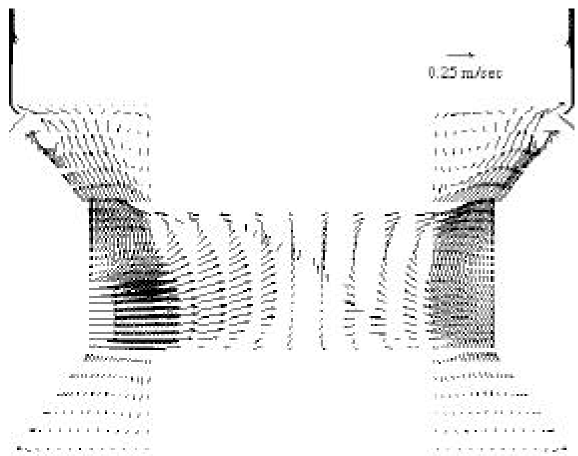




a) Thermal field along X-X'

c) Thermal field along Y-Y'





b) Velocity vectors along X-X'

d) Velocity vectors along Y-Y'

The Cross-sectional Planes of Study

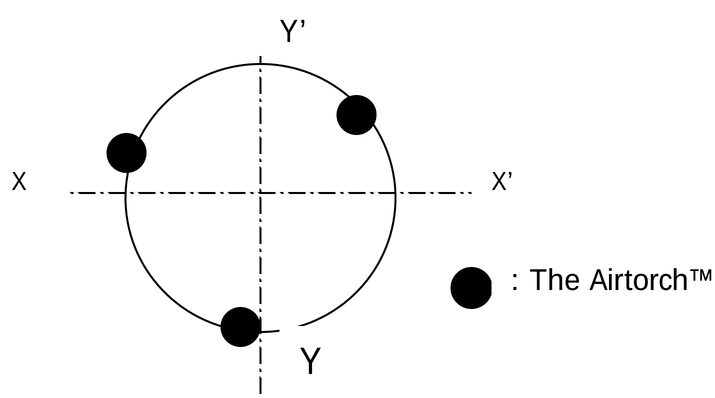


Figure 4. Thermal and flow field in the die-torch assembly at 2 hours of heating

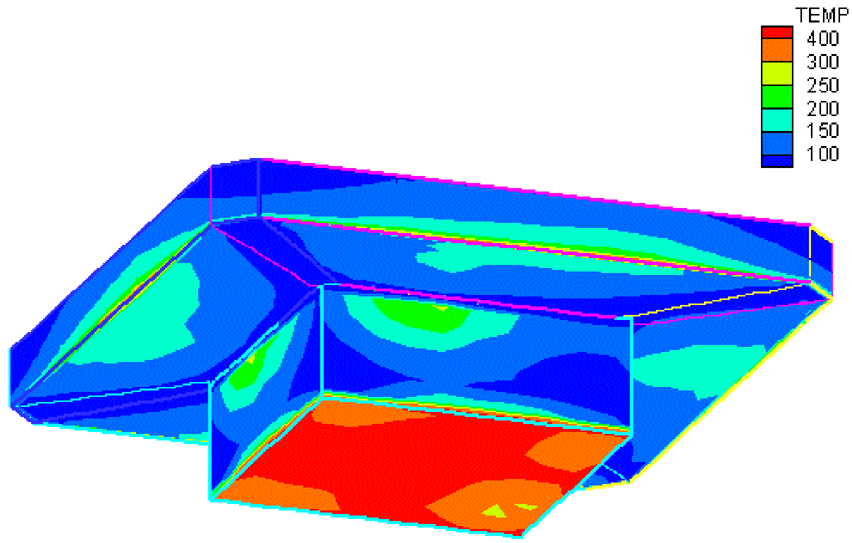


Figure 5. Thermal field in the die after 30 min. of heating by Airtorch™

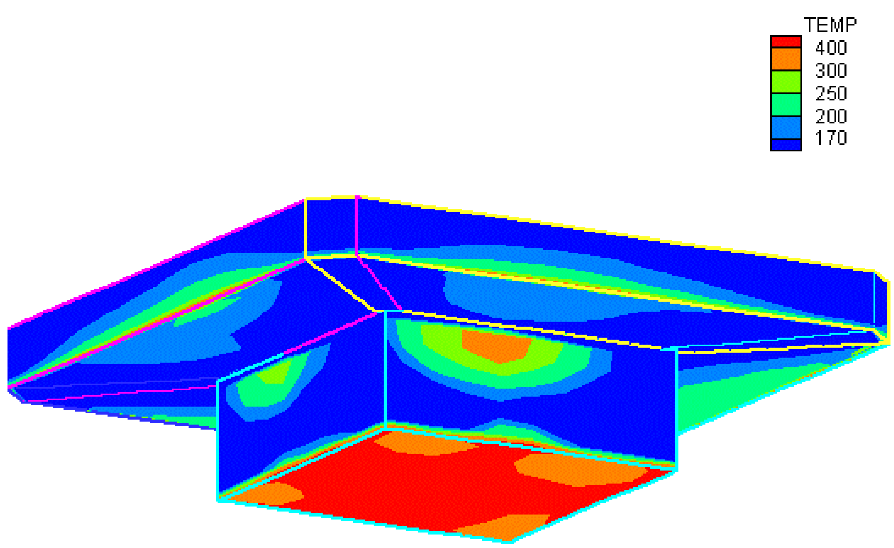


Figure 6. Thermal field in the die after 1 hr and 30 min. of heating by Airtorch™

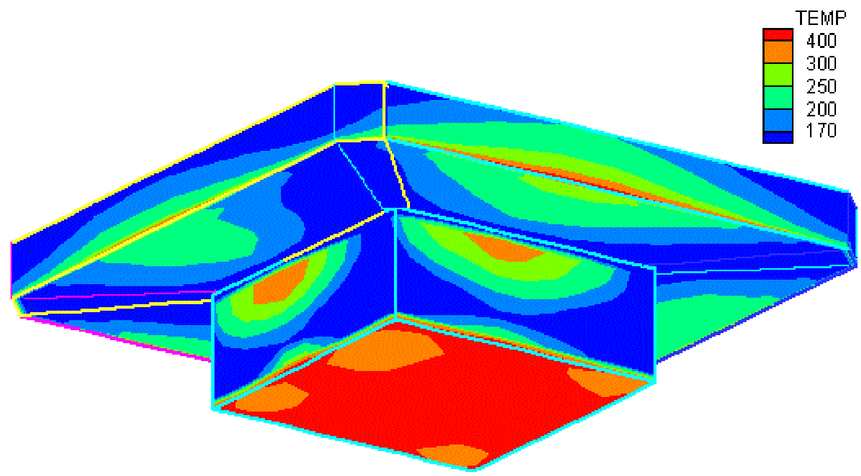


Figure 7, Thermal field in the die after 2 hrs of heating by Airtorch™

Figure 8 presents a comparative study between flame and Airtorch™ heating of the die. It can be clearly seen that a very large thermal gradient exists in the die during flame heating during the entire period of heating. When compared to the uniform heating by the Airtorch™, we note localized heating by flame resulting in hot-spots as well as a large thermal gradient as is noted from Figure 8. Additionally, on account of the large heat loss from the flame and localized heating, the heating efficiency of die by the flame configuration is considerably lower than that by Airtorch™ which ensures minimal heat loss.

Summary and Conclusion:

In this article, the heating of a die by both the Airtorch™ and flame are numerically simulated. A comprehensive approach based on the computational fluid dynamic (CFD) methods is employed for the Airtorch™ heating simulation. The predicted temperature of the die surface from the CFD-based modeling of the Airtorch™ heating is shown to be in reasonable agreement with the measured values. Using the CFD simulation as presented in this paper, the Airtorch™ parameters may be effectively optimized for any die (for forging and pressure casting) assembly leading to savings in time and cost to during manufacturing. In addition, the Airtorch™ heating is noiseless and pollution free.

With an air inlet temperature of 1200°C, it is shown that Airtorch™ ensures a near uniform heating environment of 600°C to 800°C during the entire period of heating of the die. The temperature in the die does not vary much during the entire period of heating. In contrast, during flame heating, a high thermal gradient is noted in the die and additionally there are hot-spots on the surface.

Although the case simulated in this article pertains to heating the die from the cold state (start-up), the Airtorch™ assembly may be used for "touch up" heating of the die assembly between runs, in order to bring better uniformity and consistency to the parts being manufactured.

Further information may be obtained by contacting MHI at 513-772-0404 or 513-672-3333 (fax) or by email at Airtorch™@mhi-inc.com.

References

1 K. Staples, V. Sarvepalli, M. Fu and J. A. Sekhar, US Patent 5,963, 709 Oct. 5 1999 (see also www.mhi-inc.com)

2 F.H. Jeddy, M. A. Jog, J. A. Sekhar, R. D. Markle, V. Sarvepalli, R. Burada, Advanced Materials and Processes, Oct, 1999, pg. 13-16

3 J. A. Sekhar, S. Penumella and M. Fu, Novel Heaters for Thermal Processing, eds. R. Ravindra and R.K. Singh, The Minerals, Metals and Materials Society, 1966, pg. 171-175

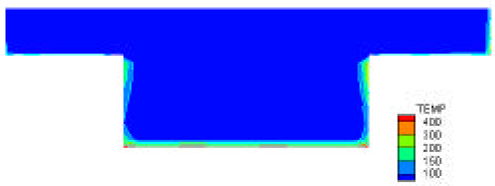
4 M. Fu, K. Staples, V. Sarvepalli, JOM, Vol.50, No.5, May 1988, pg. 42-44

5 Yogesh Jaluria Design and Optimization of thermal Systems .*The McGraw – Hill Companies, INC. International Edition 1998*

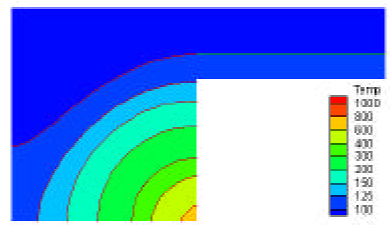
6 FASTEST-3D, Manual, Invent Computing GmbH, Erlangen, Germany, September 2000.

Nomenclature

T	**Temperature**
Q/A	**Heat Flux**
h	**Heat transfer Coefficient**
r	**Density**
s	**Stefan Boltzman constant**
e	**Emissivity**
a	**Thermal diffusivity** k/rc_p
u, v, w	**Velocities**
m	**Viscosity**
k	**Thermal conductivity**
b	**Body forces**

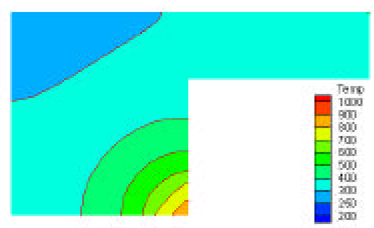


a) Airtorch™ : 30 mins.



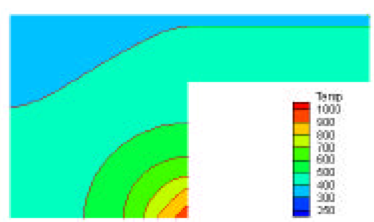
d) Flame : 30 mins.

b) Airtorch™ : 1 hr. 30 mins.



e) Flame : 1 hr. 30 min.

c) Airtorch™ : 2 hrs



f) Flame : 2 hrs

Figure 8, Comparative study of Airtorch™ and Flame heating of die