

Effects of Heat Affected Zones Temperature on the General Performance of High Temperature Vacuum Tube Furnace

A.B. Mahmud Hasan[1,2], M A Wahab[1], S.M. Guo[1]

Abstract: This paper presents details analysis of Heat Affected Zone (HAZ) in High Temperature Vacuum Tube Furnace (HTVTF) to predict fracture region in tube wall due to thermal stress from temperature variation across its thickness. A simple mathematical model is used to illustrate stress concentration arising due to thermal stresses in tube wall and HAZs. Finite element model and analysis were carried out utilizing finite element analysis commercial codes. Combination of thermal stress due to temperature difference determine fracture region. Experimental and simulation results of inside temperature of tube are observed and similar relation have been found. Observation of heat affected blocks indicates near region of HAZ. It is observed that different air flow rates have some effects in reducing thermal stress. Analysis shows that inserting a small pipe inside the first block will reduce thermal stress generation inside HAZs and eventual fracture of the vacuum tube. It is expected that this study is essential for HTVTF design.

Keywords: Finite Element Analysis, Thermal Stress, Heat Affected Zone, Heat Affected Block

1 Introduction

HTVTF (High Temperature Vacuum Tube Furnace, model number GSL1600X, manufactured by MTI Corporation, USA) is a bench-top furnace which uses $MoSi_2$ as heating element. This vacuum tube can be heated up to 1600°C (1873°K, 2912°F). The furnace is widely used for processing materials (such as ceramics), developing new materials and sintering various types of material under vacuum or gaseous condition. The metallurgical processing of zircaloy for reactor fuel pin cladding (each consisting of an array of tubes) in a high-vacuum furnace is described by Pissanetzky [1980]. Heating up metal sample in materials surface cleaning operation was conducted by Hasan et al. [2008]. The effect of calcium-bearing core wire introduced at a controlled rate on the transformations of nonmetallic inclusions with individual globular oxides that precipitated was studied by Dyudkin et al. [2002] on high temperature furnace unit.

[1] Mechanical Engineering Department, Louisiana State University, Baton Rouge, LA-70803, USA
[2] Contact address: Tel.: +1-225-382-2153; fax: +1-225-578-5924; E-mail: ahasan94@gmail.com

2 Overview of High Temperature Vacuum Tube Furnace models

To improve the performance and longevity of HTVTF, it is long been a very important research interest. Lu et al. [2006] investigates an explosion accident occurred in a HP-Nb high temperature alloy radiant furnace tube to determine the cause of the explosion. From their results it was concluded that the failure of the furnace tube was caused by high temperature. The study was carried out some heat simulation from 900˚C to 1200˚C similar to almost operation condition of HTVTF. Hamid et.al. [2005] has investigated an outlet transfer line tube of a furnace that failed by high-temperature variation inside tube wall which was due to the decrease in heat transfer from coke deposits caused wall temperature to increase during service. Pulsed heating and pressure swing technique conducted by Hasan et al. [2009] corelated with air flow operation and heating up HTVTF process. A high vacuum cylindrical furnace having the load of cylindrical tubes and supported by a carriage is described by Pissanetzky et al. [1981]. Guan et al. [2005] has conducted failure of a cracking tube that was due to bulges and circumferential cracks. Their analysis revealed that ruptures found in the tubes were caused by overheating of the tubes which caused tube bowing due to the restricted growth during the hot expansion promotes cracks.

The current investigators have found almost all alumina pipes fractured during the operation of the furnace. In order to improve furnace tube longevity and its performance - it is necessary to understand properly the phenomena that take place inside the furnace and tube wall. This study will increase understanding of thermal stress generation and failures of high temperature vacuum tube. A fractured and an actual alumina tube beside a HTVTF are shown in figure 1. The fractured tube clearly shows fracture inside the tube that may be attributed to high thermal stress generated by temperature difference in the inner and outer tube wall which caused flexural stress or buckling.

3 Steps of Operation of the furnace

To start the furnace the ceramic vacuum tube is inserted into the furnace from back side and then the screw is tightened to fix the tube's position with the holder of the furnace. The material that requires heating is placed at the middle of the tube. Porous cylindrical alumina 'Blocks' are placed inside the tube at both ends. The tube ends are closed with vacuum cover and the heater is turned on. The air within the furnace and the tube, eventually heats up due to convection by the electric heater. The major portion of the heat will dissipate by natural convection to the air within the heater and the tube, while its minor portion conducts through the furnace to the lab temperature. The heat then conducts through the cylindrical inner wall of the tube and will dissipate to the air inside the tube. Figure 2 shows a HTVTF with the necessary accessories attached with it.

4 Model Development

The model presented in this study address HTVTF in a realistic way using multiphysics simulation software Comsol®[2005]. The results from the simulation will be beneficial for further and more complete analyses of the performance of HTVTF. The main objectives of research are to: (i) study in detail all the physical phenomena that govern the operation of a HTVTF, (ii) pass air with different flow rates to find out critical thermal stress, (iii) address the complex phenomena of fracture in HTVTF and (iv) finally, to study the relaxation of the heat affected zone (HAZ) of the tube by inserting a small diameter pipe inside cylindrical block to redistribute the heat inside the furnace.

A symmetric 2D numerical model of HTVTF with alumina tube at the interface of block and furnace lower wall, cylindrical porous alumina blocks at two ends inside tube and electric heater at the top are shown in figure 3. For this 2D symmetric model is chosen to save computation time and to assume that the bottom as well as the top part of the furnace will act similarly; with symmetry existing for geometry, loads, and boundary conditions. Cylindrical blocks help keeping heated air inside the tube and heat cannot dissipate/escape through the vacuum sealing cover of the tube or lower the furnace temperature.

The various dimensions for the HTVTF are shown in table 1 as mentioned by MTI Corporation.

5 Numerical Model and Governing Equations

The FE (Finite Element) meshing of the numerical model is shown in figure 4. Condensed meshing is used at the interface region of the blocks and the surrounding area of the tube as these regions are affected by fracture due to excessive thermal stress generation by temperature difference which is known as HAZs.

This model involves mass conservation, natural convection, general heat transfer and thermal stress module. Thermal stress is conducted using linear coefficient of thermal expansion assumption. For simulation, the values for various constants and parameters are shown in table-2 at assuming average temperature inside furnace is at 1700 °K. Non-isothermal flow assumption is used inside the furnace and the tube as the furnace temperature will vary in different locations. For flow

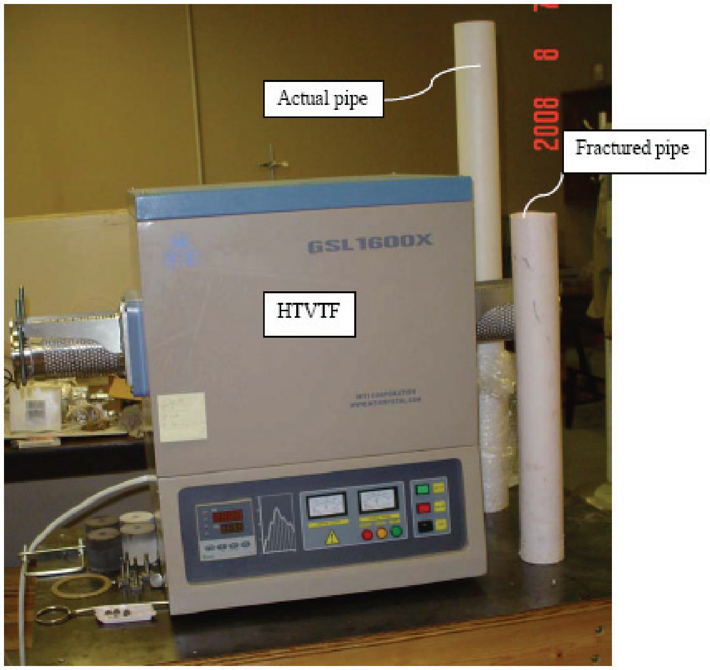

Figure 1: Fractured tube with actual tube beside HTVTF

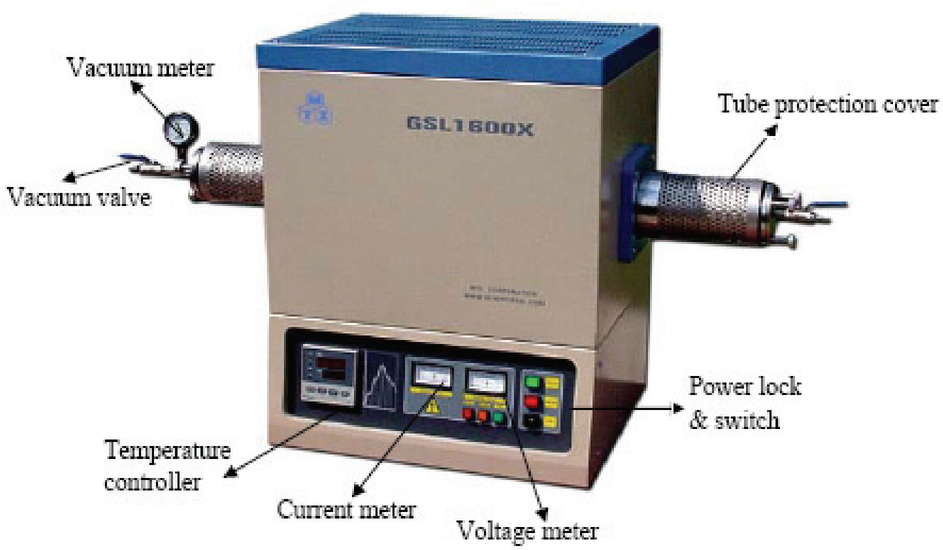

Figure 2: HTVTF showing different parts Comsol Multiphysics user guide [2005]

condition mass conservation equation is used.

$$\vec{\nabla} \bullet (\rho \vec{u}) = 0 \tag{1}$$

It is assumed that heat transfer will occur from higher to lower temperature region of air inside the furnace and the tube by natural convection and these are shown below:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = g\beta(T - T_\infty) + \nu\frac{\partial^2 u}{\partial y^2} \tag{2}$$

Here, $\beta (= \frac{1}{T})$ is volumetric thermal expansion coefficient (/°K) and $\nu (= \frac{\mu}{\rho})$ is kinetic viscosity of air (m^2/s). Values of various parameters

Table 1: Components of HTVTF dimensions MTI Corporation Inc. [2006]

Property	Value (mm)
Furnace length	550
Furnace width	270
Air region (inside furnace) width	35
Air region length	270
Tube Length (L)	1000
Tube thickness (t)	5
Tube inside radius®	35
Block length	130
Block radius	35
Small diameter pipe (inserted)	1

Table 2: Constants and parameters used in numerical simulation www.matweb.com

Variable	Definition	Value
$Theater$	Temperature of heater	1872 °K
$T\alpha$	Ambient Temperature	303 °K
$\rho_{alu\min}$	Density of alumina	3900 kg/m^3
$c_{p,alu\min}$	Heat capacity of alumina	1050 J/kg-°K
$EAlumina$	Modulus of Elasticity of alumina	3.5×10^{11} Pa
$\kappa_{alu\min,furnace}$	Thermal conductivity of alumina in furnace	39 W/m-°K
α	Thermal expansion coefficient of alumina tube	9.6×10^{-6}/°K
ε	Poisson's ratio of alumina	0.33
$c_{p,air}$	Heat capacity of air	1189 J/kg-°K
κ	Thermal conductivity of air	0.082 W/m-°K
μ	Dynamic Viscosity of air	4.96×10^{-5} Pa-s
ρ_∞	Density of air at ambient temperature	0.2679 kg/m^3
g	Acceleration due to Gravity	9.8 m/s^2

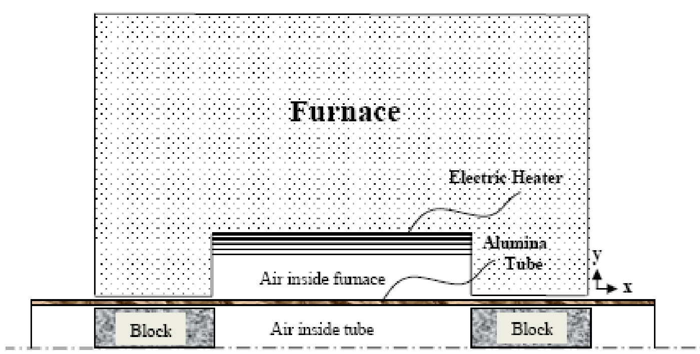

Figure 3: Vacuum tube furnace with porous blocks inside tube geometry at both entrances

are shown in tables-1 & 2. General heat transfer equation is used in every domain. Mostly heat conduction equation is used in the tube and furnace which are solid substance and the convection equation is used in the domain which contains air.

$$\vec{\nabla}\bullet(-\kappa\vec{\nabla}T)+\rho c_p\vec{u}\bullet\vec{\nabla}T=0 \tag{3}$$

Coupling of thermal stress and temperature data

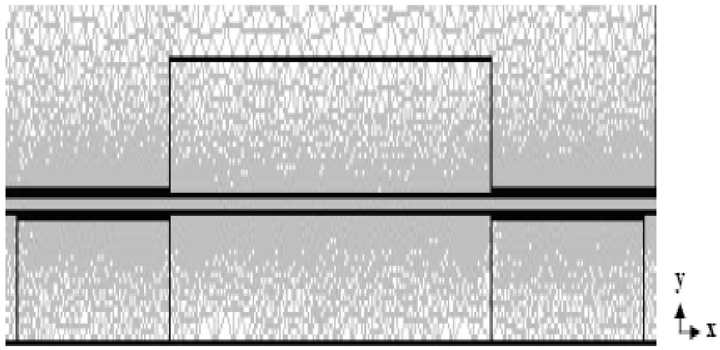

Figure 4: Meshing of the different furnace domains

is necessary to use thermal expansion of tube due to temperature variation within the tube. The following simplified equation for linear thermal expansion is used to couple between the two data:

$$\sigma = E\alpha\Delta T \quad (4)$$

where, σ is total thermal stress (Pa), E is modulus of elasticity (Pa), α is Coefficient of thermal expansion (/°K), and ΔT is temperature difference (°K).

6 Management of boundary conditions

Boundary conditions have been defined as upper wall of air inside furnace at heater temperature condition which is 1873°K. For the bottom part symmetric boundary condition for momentum equation and zero heat flux condition for heat equation have been considered. Most of the boundary conditions have been considered as continuity boundary conditions to get value from the surrounding domains. No-slip flow boundary conditions have been considered for wall surfaces.

7 Results and Discussion

Figure-5 illustrates temperature profile of tube considering natural convection inside furnace and tube. Air inside the high temperature from the middle of the furnace convect by natural convection and distribute both ends of tube. Cylindrical blocks are necessary to avoid heat loss at the two ends of tube. Blocks are placed at the inside of the tube near HAZs, while metal heating and processing were conducted at the middle.

New blocks as well as heat affected blocks have been shown in figure-6. From observation it is found that blocks are porous cylindrical short length alumina materials. Figure-7 shows temperature profile with these blocks inside tube. As $MoSi_2$ heater is placed near the top part of the furnace so high temperature exists at the middle of the furnace. Two HAZs for higher temperature difference between inner and outer wall of tube have been detected and are also shown in figure 7. It is observed that lab alumina tubes fractured in these zones. Fractured pipe with operation of actual pipe in HTVTF is shown in figure-8 to describe more about operation of HTVTF and cause of fracture.

To verify simulation result, comparison between simulation results and experimental data (provided by MTI Corporation) are made and shown in figure 9. Temperature data for the inner wall between HAZs along the tube have been calculated from the simulation and is shown in this figure 9. Data indicates very high temperature at the middle of the tube which decreases gradually at the two HAZs of tube due to heat convection from electric heater to HAZs when blocks are present inside tube. A good correlation is found between experimental and simulation data which indicates validity of simulation techniques and results.

Later air, which is produced from metal heating/sintering during operation at lab temperature condition, is passed through the left inlet side of the tube for the purpose of removing heated air from the furnace. Different air flow rates have been passed to find out temperature vari-

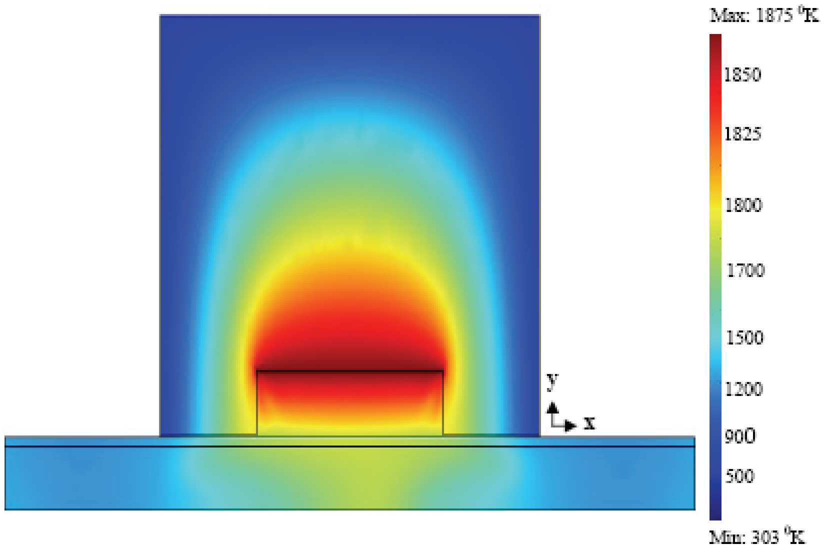

Figure 5: Temperature profile due to natural convection inside the furnace without porous cylindrical alumina blocks

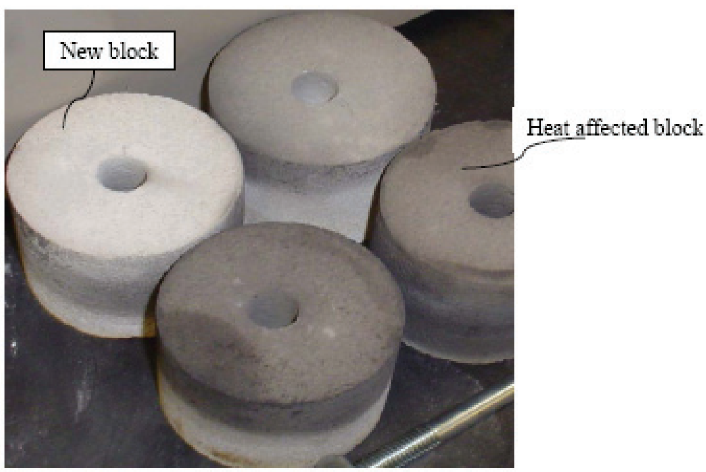

Figure 6: New and heat affected porous cylindrical Blocks

ation/difference in HAZs to find out reasonable flow rate for stresses relax in HAZs. Figure 10 shows temperature profile inside a furnace for inlet air flow condition of 5 ml/min. Although air temperature was lower in the entrance compared to inside of furnace, air eventually heats up and gets higher temperature from the furnace. Temperature variation for inner and outer wall alumina tube is very important to analyze thermal stress. Calculation shows the thermal stress in the HAZ-2 is less compared to the HAZ-1. It has also observed that that, the tube generally fractures in HAZ-1 at the time of operating this furnace. According to data provided by MTI Corporation it is found that maximum flexural strength of alumina tube at 1700 °K (assuming average furnace temperature at that temperature) is 55 MPa. Therefore, it is important not to exceed that maximum stress value while operating this furnace.

To blow out the heated air so that it cannot accumulate inside the alumina, a small pipe with a diameter of 1 mm is inserted inside the block and is shown in figure 11. This pipe blows heated air to the HAZ-2. This pipe is inserted from the in-

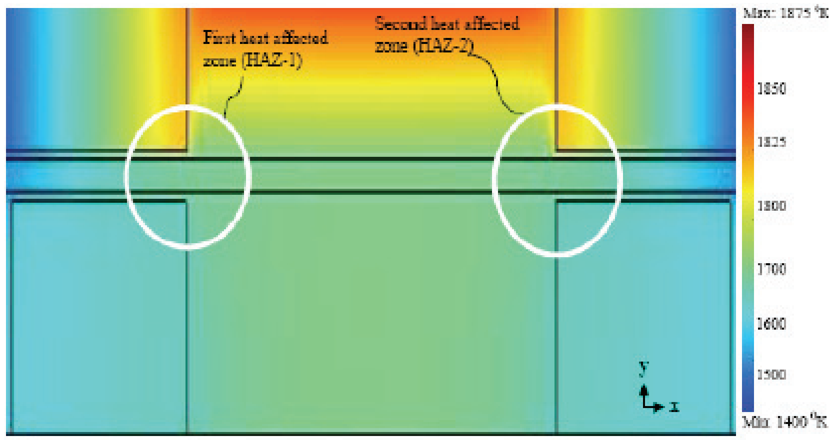

Figure 7: Temperature profile with cylindrical blocks, heat affected zones and no inlet gas flow condition

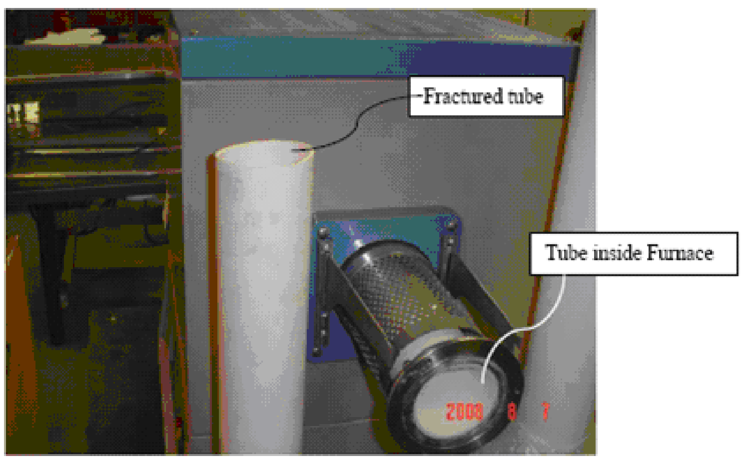

Figure 8: Fractured alumina tube

let side to the end of first block inside the alumina tube. The air inside this small pipe will take heat from the heated tube and will blow hot air mostly on HAZ-2. Due to higher temperature from hot air flow on HAZ-2, the temperature difference can be reduced for inner side of tube wall as shown in figure 11 which also reduces risk of failure of high temperature vacuum tube.

8 Conclusion

Analysis of HAZ in HTVTF to predict fractured region in tube wall due to thermal stress from temperature variation is conducted. A simple mathematical model using natural convection, later forced convection and thermal stress is used to illustrate inside tube wall and heat-affected-zones (HAZ) condition. Finite element model and analysis were carried out utilizing finite element analysis commercial multiphysics software Comsol®. Experimental and simulation results of inside temperature of tube show similar behavior and results. To find out critical thermal stress in HAZs 1 mm small diameter pipe was inserted inside the first cylindrical block from the left hand end of vacuum tube inlet to flow hot air of maximum 35 ml/min on HAZ-2. This condition protects from thermal stress in HAZs. It is expected that this investigation will increase understanding of HTVTF design.

Acknowledgement: This study is based upon work supported by the NASA/EPSCoR under grant number NASA/LEQSF (2007-10)-Phase3-01. The authors greatly acknowledge for the fi-

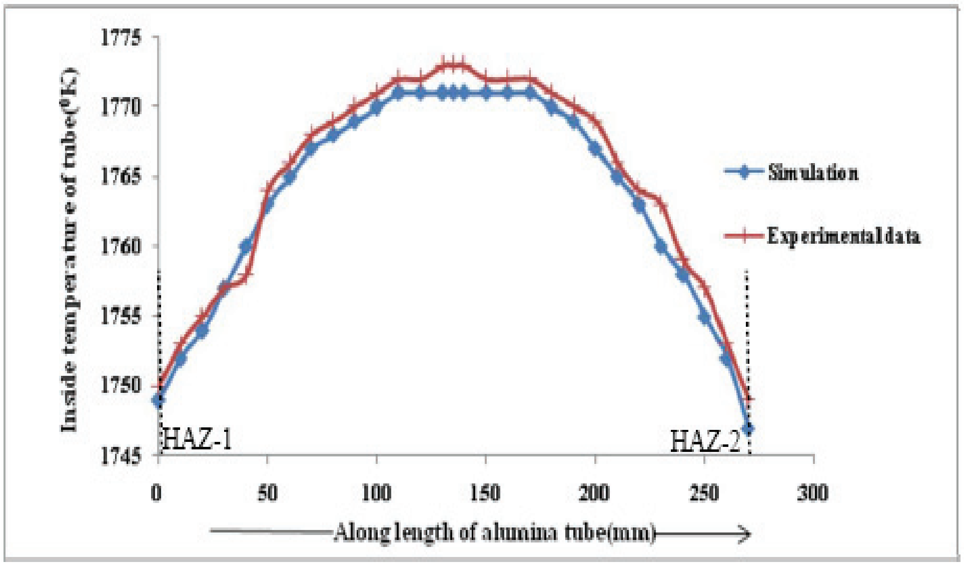

Figure 9: Experimental and simulation result of inside temperature of the tube between HAZs

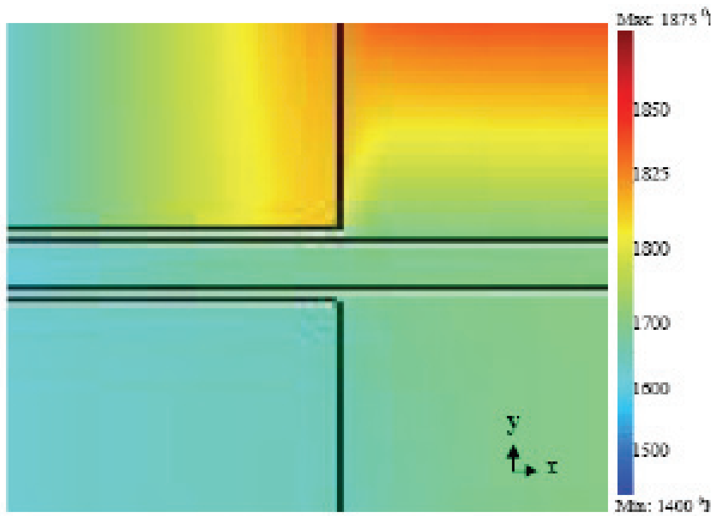

Figure 10: Temperature profile with inlet air flow rate condition of 5 ml/min

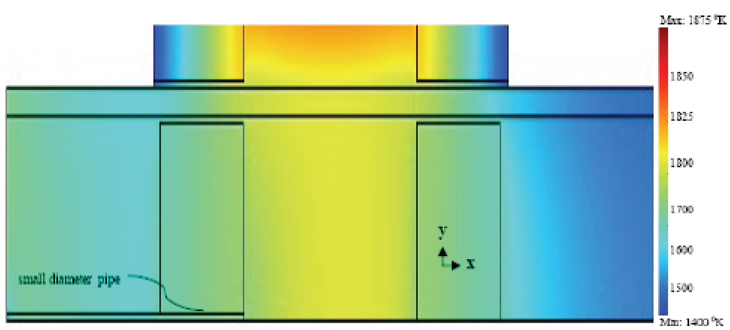

Figure 11: Temperature profile for the furnace while a small pipe is inserted inside the block

nancial support of this work.

References

Comsol Multiphysics user guide (2005): Stockholm, Sweden.

David, R, Nettles, O, Liu, R, Hasan, A.B.M., Guo,S.M., Wahab, M. A. (2008): Metal Surface Cleaning Using Electro-Plasma Process, Symposium of Fracture Mechanics of Welded Structures and Surface Coatings and Surface Cleaning Mechanics, First American Academy of Mechanics Conference, June 17-20, New Orleans, LA, USA.

Dyudkin, D.A., Grinberg, S.E., Grabov, A.V., Nazarov, S.N., Motrenko, S.A., and Pogorelova, I.G. (2002): Effect of Calcium on the Quality of Tube Steel, *Metallurgist*, Vol. 46, Nos. 11-12.

Guan, K, Xu, H.; Wang, Z. (2005): Analysis of failed ethylene cracking tubes, *Engineering Failure Analysis*, v 12, n 3, p 420-431.

Guo, S.M., Hasan, A.B.M. (2009): Proton Exchange Membrane Fuel Cell High Carbon Monoxide Tolerance Operation using Pulsed Heating and Pressure Swing, *Journal of Fuel Cell Science and Technology*, Vol.6, No.1, 011022.

Hamid, U.A., Tawancy, H.M., Mohammed, A.I., Al-Jaroudi, S.S., Abbas, N.M. (2005): Failure of ethylene furnace outlet transfer line due to overheating, *Journal of Failure Analysis and Prevention*, v 5, n 4, p 54-61.

Lu, S., Zhang, P., Qin, C., Wang, X., Luo, F., Zhou, J. (2006): The analysis on causes of rupture of a HP-NB high temperature alloy radiant furnace tube, Proceedings of 2006 ASME Pressure Vessels and Piping Division Conference, ASME PVP2006/ICPVT-11 Conference.

Materials properties data from www.matweb.com.

MTI Corporation Inc. (2006): user manual, Richmond, CA-94804, USA.

Pissanetzky, S. (1980): Numerical simulation of the transient temperature distribution inside a close-packed array of cylindrical tubes during heating and cooling under high vacuum, *Nuclear Engineering and Design*, Volume 56, Issue 2, Pages 359-368.

Pissanetzky, S., Cingolani, H., Volpi R., Almagro, J. C. (1981): Numerical simulation of the transient temperature distribution within the cladding material during annealing in a high vacuum furnace, *Nuclear Engineering and Design*, Volume 65, Issue 1, Pages, 141-150.