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BOILING POOL TEMPERATURE HISTORY OF STATIONARY STEEL SHEETS IMPINGED BY MULTIPLE PIPE LAMINAR JETS

T. O. Onah[*], S. Idogwu[2] and I. D. Oghonna[3]

1, 2, and 3: Department of Mechanical and Production Engineering, Enugu State University of Science and Technology Enugu, Nigeria.
Corresponding Author: Okechukwutm@yahoo.com

Abstract -Investigation of temperature history of pool boiling mechanism using water Jet Impingement System has been carried out. The methodology undertaken for this research involved design and construction of experiments using a pilot scale run-out table with stationary plates in Metallurgical and Material Laboratory, ESUT, Enugu Nigeria. The cooling was investigated by pipe water planar diameters of 20mm and 45mm by impingement water jets of 30 number holes and impingement gaps of 40mm and 70mm. The cooling rate was fastest at grid G1 at the top surface, followed by grid G2, G3, G4 and the least at grid G5 at the bottom surface. The hot plate was cooled softly from 469^{o}C to 438^{o}C and 500^{o}C to 458^{o}C, at high temperatures above the boiling point of water. The temperature history of impingement cooling nearly show the same cooling mode from the film boiling to nucleate boiling, from cooling surface temperature range of 438^{o}C to 500^{o}C, and cooled linearly from 300^{o}C to 260^{o}C by finite temperature history across the workpiece. This assisted multiple pipe laminar jets impinging onto a stationary hot steel plate and improved the microstructure of cooled hot plates. The cooling rates at the film boiling modes are : 7.32^{o}C/sec at D= 20mm and H=40mm, 11.25^{o}C/sec at D =20mm and H = 70mm, 10.40^{o}C/sec at D= 45mm and H= 40mm, and 5.65^{o}C/sec at D 45mm and H =70mm respectively. Moreover, the values of cooling rates at the nucleate boling regimes are; 32.23^{o}C/sec at D= 20mm and H = 40mm, 36.31^{o}C/sec at D =20mm and H = 70mm, 34.48^{o}C/sec at D =45mm and H =70mm, and 32.26^{o}C/sec at D 45mm and H =70mm respectively.. Similarly, the rate of cooling under nucleate boiling was 36.31^{o}C/sec at diameter, D, of 20mm and impingement gap, H, of 70mm. It was established that the rate of cooling was better achieved with smaller jet pipe diameters and longer impingement gap. This therfore showed faster rate of cooling at nucleate regime

Keywords: Impingement cooling, planar jet, impimgement gaps, pipe diamters, temperatures profile, pool boiling, film boiling and nucleate boiling.

1.0 Introduction

The desired material structures are obtained by the rapid cooling of hot steel plates from approximately 900°C to a predetermined coiling temperature using water jet impingement Monde *et al.*, (2002). The fig. 1 shows a schematic of the temperature profile of a hot steel plate during water jet cooling. However, the temperature of the hot steel is far above the boiling temperature of the liquid. The steel is cooled softly at high temperatures of the hot plate because a stable vapor layer is formed between the water and steel. Such a boiling mode is called film boiling. As the cooling proceeds, the vapor film becomes thin and unstable. Direct contact between the water and solid occurs locally as well as temporally; that is, transition boiling occurs in the range between the points called the minimum heat flux (MHF) and critical heat flux (CHF). The boiling mode soon shifts to strong nucleate boiling where numerous vapor bubbles are generated at the liquid/solid interface instead of the vapor film. The heat removal rate is very large in the transition or strong nucleate boiling regime. Thereafter, the temperature variation of the solid reduces because the boiling becomes weak.

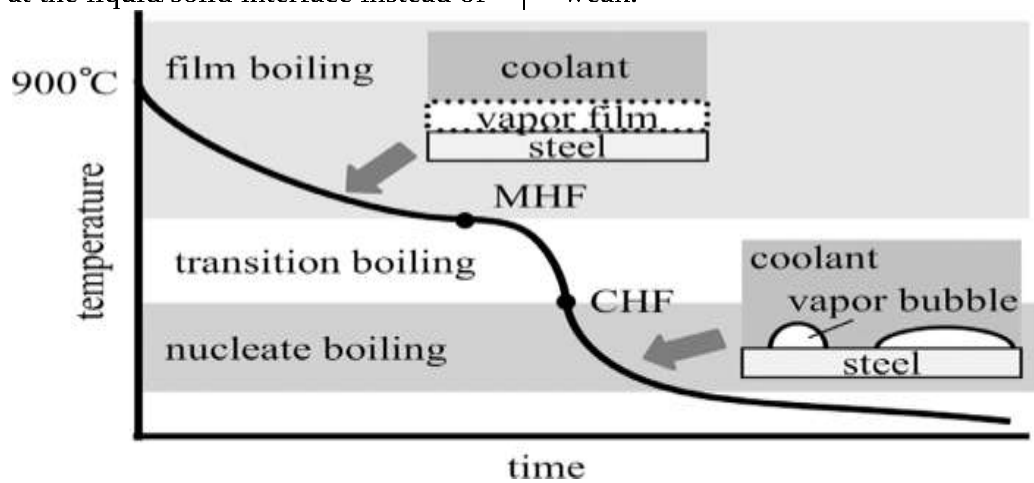

Fig. 1: Schematic of temperature cooling history of cooled hot-rolled steel plate by water jet impingement. (Hammed, *et al.*, (2014).

On the run-out table cooling system, when the cooling temperature of the hot steel is present in the transition or strong nucleate boiling regime, precise temperature control of the plate is difficult because of a large temperature variation of the plate. Accurate heat transfer data in these boiling regimes are required. Many experimental works have been undertaken concerning the boiling heat transfer involving impinging water jets, Hammed, *et al.*, (2014). Many of these studies were conducted considering single-jet impingement onto a stationary or moving hot plate. However, in actual Run-Out-Table (ROT) cooling, pipe planar array jets impact onto a stationary hot steel plate Gradeck, *et al.*, (2009). It is considered that the stationary or moving hot steel plate and the flow interaction due to multiple-jet impingement produce complicated hydrodynamic behavior of water and heat transfer characteristics. However, these factors cannot be analyzed by performing experiments involving single-jet impingement onto a stationary or moving hot steel plate. Also studies have analyzed single-jet impingement onto a stationary hot steel plate as specified by Gradeck, *et al.*, (2009).

In addition, Monde *et al.*, (2002), and Haraguchi, examined multiple pipe laminar jets impinging onto a stationary hot steel plate. They also noted the boiling heat transfer on a hot moving plate, caused by multiple impinging water jets in rows. They found that the moving velocity of steel sheets, the spacing of nozzles, and the number of jets had some influence on the heat transfer rates in jet impingement zones. However, fundamental knowledge of the hydrodynamics of a coolant and heat transfer characteristics in such a situation is lacking. The motivation of the present study tries to resolve these issues by means of laboratory-scale experiments.

This work therefore tries to investigate the temperature profile of pool boiling. The heat transfer mechanism of multiple pipe planar water jets impinging onto a stationary hot steel plate by means of laboratory-scale pilot plant system experiments was studied

2.0 Materials and Methods

2.1 Description of water jet impingement cooling system

Fig. 2 shows a schematic diagram of the pilot scale run-out table (ROT) facility designed, fabricated and installed at the Metallurgical and Material Engineering Laboratory (MMEL), ESUT.

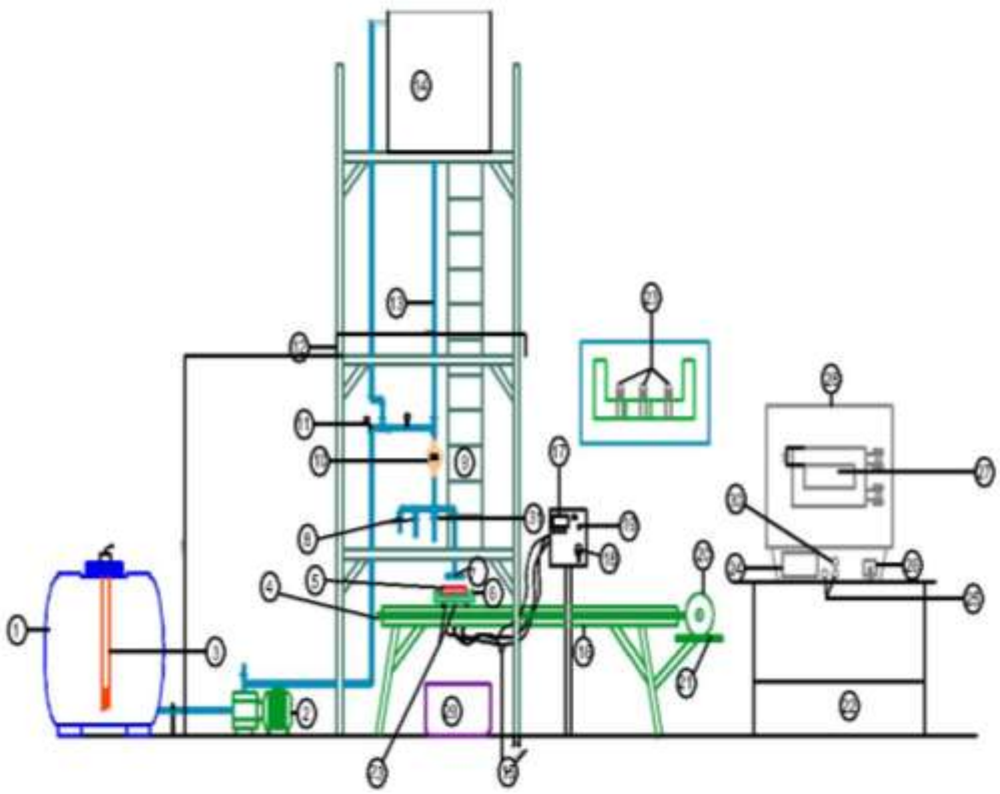

Fig. 2: Schematic diagram of the pilot plant.

KEYS:

Parts of the machine

1. Water tank, 2. Electric pump, 3. Heater, 4. Conveyor screw, 5. Work piece, 6. Work piece bed, 7. Impingement nozzle, 8. Ball gauge socket, 9. Ladder, 10. Flow meter, 11. Pressure meter, 12. Tower, 13. PVC pipe, 14. Reservoir, 15. Thermocouple wire, 16. Motorized Screw conveyor, 17. Thermocouple control panel, 18. Regulator, 19. Lock, 20. Electric motor, 21. Electric motor support and 22. Furnace support.

Heating was done within the electric furnace to a temperature of 920^{o}C in Metallurgical and Material Engineering Laboratory (MMEL), and transported by a motorized powered conveyor drive system of 0.75kw of 1500rpm to from the furnace to the cooling tower for the cooling.

The cooling system features a closed water loop where 0.945m^3 (945 liters) of water. The surface temperatures, water temperatures, impingement gaps and flow rates were controlled. An ATLAS (ATP 60) water pump that provided total water flow rates of 60L/min and assisted impingement water through the impingement jet nozzle to the hot plate. An electric heater of 9kw of 330volts was used to adjust the temperature of water between 10-70^{o}C. The water temperature readings were taken by a mercury in bulb thermometer. However, curtain nozzle of 12x12 mm by 30x 90mm with 0.8 mm of 30 number holes was used and readings were recorded with a control panel. However, two pipe diameters of 20mm and 45mm, and impingement gaps of 45mm and 70mm were used. The initial temperatures of the hot plates were varied from 438^{o}C to 500^{o}C. The heat transfer characteristics were evaluated by solving heat by conduction, boiling and convectional model by a one dimensional explicit finite temperature development method, using the measured temperature profile as boundary conditions.

2.2 Discretization of temperature history development across the thickness of 120mm

Fig. 3 shows energy balance of both conditions for the top surface and bottom surface under adiabatic conditions, across the thickness.

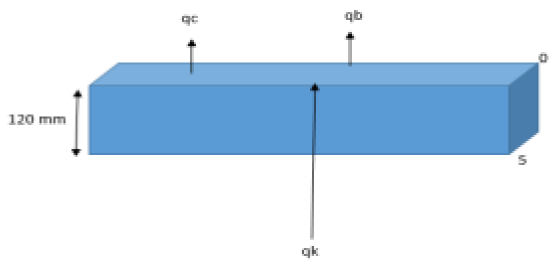

Fig. 3: Energy balance on the work piece at bottom and top

The governing Equation of the control volume of the energy balance of Fig. 3 was solved by assuming the temperature at the bottom to be constant. Therefore rate of change of temperature $\frac{\partial T}{\partial x} = 0$. Then subject to conditions of heat transfer by convection (q_c) and boiling (q_b) applied at the top surface; the boundary condition is solved by equating the heat transfer by conduction (q_k) from the bottom to be equal to heat transfer by convection and heat transfer by boiling (evaporation).

Thus, $q_k = q_c + q_b$ **(1)**

where $q_k = -kA\frac{\partial T}{\partial x}\Big|_{x0}$ = conductive heat transfer (W) **(2)**

$q_c = Ah(T_0 - T_\infty)$ = convective heat transfer (W), and **(3)**

$q_b = h_{fg}$ = heat outflow due to evaporation of cooling water (W). **(4)**

Thus Equ. (3.10) can be expanded as Equ. (3.14), as;

$$-k\frac{\partial T}{\partial x}\Big|_{x0} = q_k = h(T_0 - T_\infty) + h_{fg} \quad \textbf{(5)}$$

Where , is the mass flow rate and h_{fg}, is the latent heat of vaporization of the water

For one- dimensional treatment of Finite Difference

The steps employed were:

1. Computing T_o for each time period
2. Computing for T_1 to T_5 using the Finite Difference treatment
3. Computing for A= λB + λC+λD

The stencil for the explicit finite difference method for the heat Equ. of step 3 is shown in Fig. 4, as;

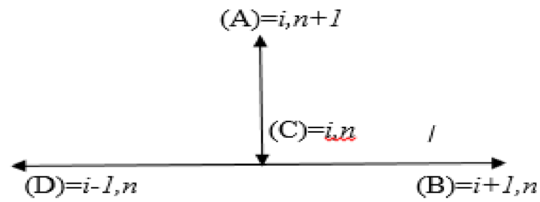

Fig. 4: Stencil for explicit finite difference of heat Equation of balanced energy

From the stencil for the explicit finite method above, using the nodal point at (A) =i, n+1, would yield the expression

$$A = \lambda B + \lambda C + \lambda D \quad \textbf{(6)}$$

By substituting the values of A, B, C, and D in Equ.6), gives Equ. (7), as;

$$T_{i,n+1} = \lambda T_{i+1,n} + (1 - 2\lambda)T_{i,n} + \lambda T_{1-i,n} \textbf{(7)}$$

Where $\lambda = \frac{\alpha \Delta t}{\Delta x^2}$

for steel of Mn< 0.1≤0.8% and Si ≤ 0.1%;

α = thermal diffusivity of steel=1.775 x 10^{-6} m^2/s (Theodora *et al.*, 2012)

The temperature across the 120 mm thickness is sectioned into five developments for each of 24mm as shown in Fig. 5 as;

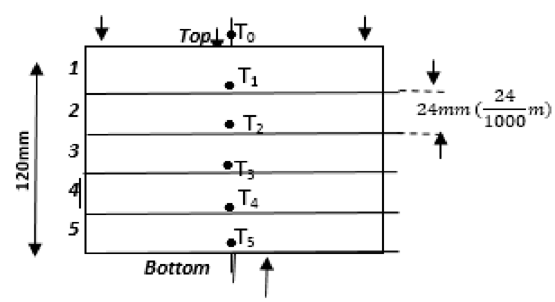

Fig. 5: Sketch of temperature across the thickness from top to bottom plate

For the 1 –D "EXPLICIT F.D" to converge to a good solution; the stability is based on the conditions that

{ 0<λ≤ ½} (Crank, 2015)

If α = thermal diffusivity of steel = 1.775 x 10^{-6} m^2/s

For Δx = 24/1000, and

Δt = 30 sec for the interval of each time used, Solving for λ in the Equ. (8) of

$T_{i,n+1} = \lambda T_{i+1,n} + (1-2\lambda)T_{i,n} + \lambda T_{1-i,n}$, for **(8)**

$$\lambda = \frac{\alpha \Delta t}{\Delta x^2} = \frac{1.775\ x\ 10^{-6}\ x\ \Delta t}{0.024^2}$$

$$\lambda_{@30\,\sec interval} = \frac{1.775\ x\ 10^{-6}\ x\ 30}{0.000576} = 0.092$$

The condition for convergence therefore becomes $\left\{0 < 0.092 \leq {}^{1}/_{2}\right\}$

Thus, Equ. (8) gives Equ. (9), as;

$$T_{i,n+1} = 0.092T_{i+1,n} + 0.816T_{i,n} + 0.092T_{1-i,n} \quad \textbf{(9)}$$

3.0 Results and Discussion

3.1. Results for Temperature-time cooling profile of diameter D=20mm and impingement gap H=40mm

Fig.4 shows the temperature –time cooling profile for pipe diameter 20mm and impingement gap 70mm. Also the rate of flow is fastest at grid G1 at the top surface, followed by grid G2, G3, G4 and the least at grid G5 at the bottom surface. The hot plate is cooled softly from 438°C at high temperature above the boiling point of water and falls below 300°C. The boiling mode flow rates of 11.25°C/sec starts from F1 to F2 the film boiling because stable vapour layer is also formed between water and the hot plate with F2 at minimum heat flux (MHF). F2 to F3 depicts transition boiling in the range of MHF and CHF because direct contact occurs between the hot plate and water. Here vapour film becomes thin and unstable and terminates at critical heat flux (CHF). The boiling mood flow rate of 32.31°C/sec then shifts to strong nucleate boiling where numerous vapour bubbles are generated at the liquid –vapour interface instead of the vapour film.

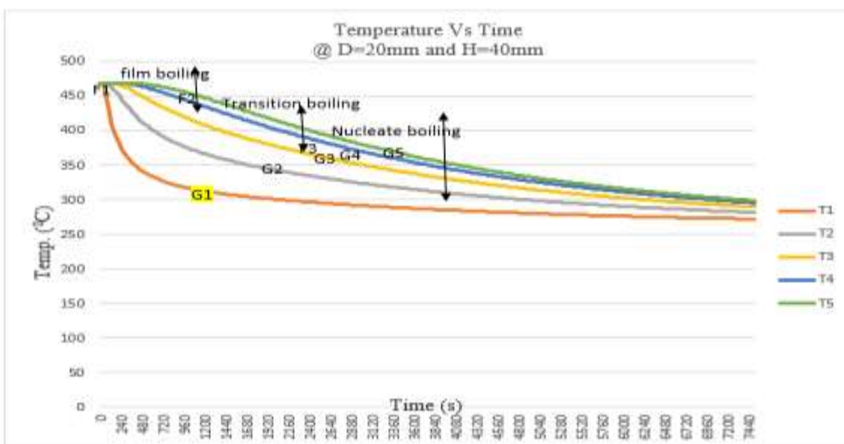

Fig.6.4: Temperature-time cooling profile on run - out table for D = 20mm and H=40mm

3.2. Results for Temperature-time cooling profile of diameter D=20mm and impingement gap H=70mm

Fig.5 shows the temperature –time cooling profile for pipe diameter 20mm and impingement gap 70mm. Also the rate of flow is fastest at grid G1 at the top surface, followed by grid G2, G3, G4 and the least at grid G5 at the bottom surface. The hot plate cooled softly from 438°C at high temperature above the boiling point of water and falls below 300°C. The boiling mode flow rates of 11.25°C/sec starts from F1 to F2 the film boiling because stable vapour layer is also formed between water and the hot plate with F2 at minimum heat flux (MHF). F2 to F3 depicts transition boiling in the range of MHF and CHF because direct contact occurs between the hot plate and water. Here vapour film becomes thin and unstable and terminates at critical heat flux (CHF). The boiling mood flow rate of 32.31°C/sec then shifts to strong nucleate boiling where numerous vapour bubbles are generated at the liquid –vapour interface instead of the vapour film

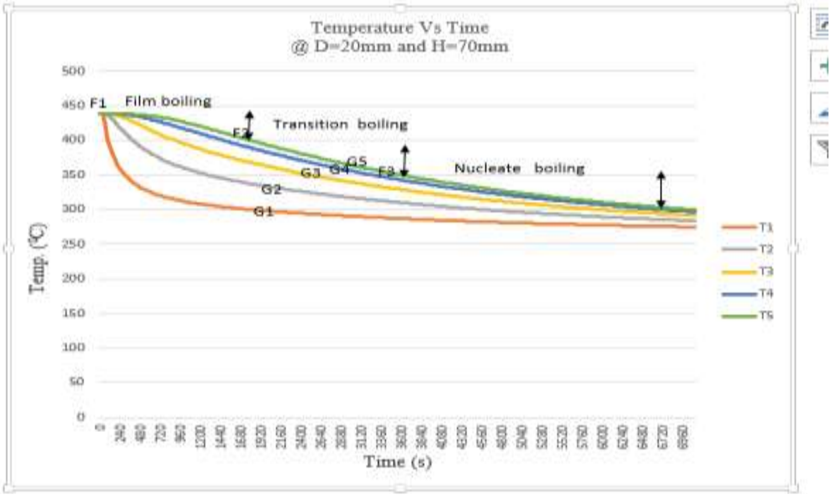

Fig.5: Temperature-time cooling profile on run - out table for D= 20mm and H=70mm

3.3. Results for Temperature-time cooling profile of diameter D = 45mm and impingement gap H=40mm

Fig..6 depicts the temperature –time cooling profile for pipe diameter 45mm and impingement gap 40mm. The rate of flow is seen fastest at grid G1 at the top surface, followed by grid G2, G3, G4 and least at grid G5 at the bottom surface. The hot plate is equally seen cooled softly here from 500°C at high temperature above the boiling point of water and falls below 300°C. Here, the flow rates of 10.40°C/sec starts from F1 to F2 the film boiling because stable vapour layer also occurred between water and the hot plate with F2 at minimum heat flux (MHF). F2 to F3 depicts transition boiling in the range of MHF and CHF because direct contact occurs between the hot plate and water. Here vapour film becomes thin and unstable and terminates at critical heat flux (CHF). The flow rate 34.81C/sec soon shifts to strong nucleate boiling where numerous vapour bubbles are generated at the liquid –vapour interface instead of the vapour film.

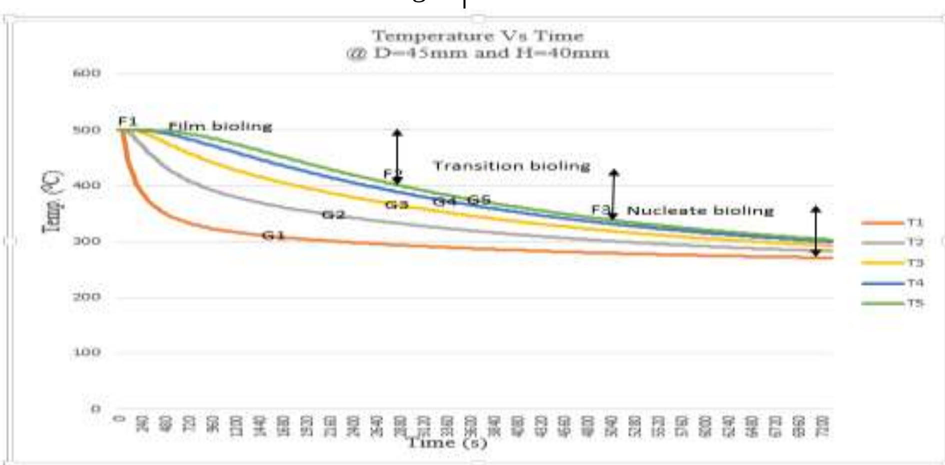

Fig.6: Temperature-time cooling profile on run - out table for D= 45mm and H=40mm

3.4 Results for Temperature-time cooling profile of diameter D = 45mm and impingement gap H=70mm

Fig. 7 depicts the temperature –time cooling profile for pipe diameter D = 45mm and impingement gap H = 70mm. Again cooling rate is faster at grid G1 at the top surface, followed by grid G2, G3, G4 and least at grid G5 at the bottom surface. The hot plate is also cooled softly from 458°C at high temperature above the boiling point of water and falls below 300°C. The flow rate of 5.65 °C/sec boiling mode starts from F1 to F2, the film boiling because stable vapour layer is formed between water and the hot plate with F2 at minimum heat flux (MHF). F2 to F3 depicts transition boiling in the range of MHF and CHF because direct contact occurs between the hot plate and water. Here vapour film becomes thin and unstable and terminates at critical heat flux (CHF). The boiling mood flow rate of 32.26°C/sce soon shifts to strong nucleate boiling where numerous vapour bubbles are generated at the liquid – vapour interface instead of the vapour film.

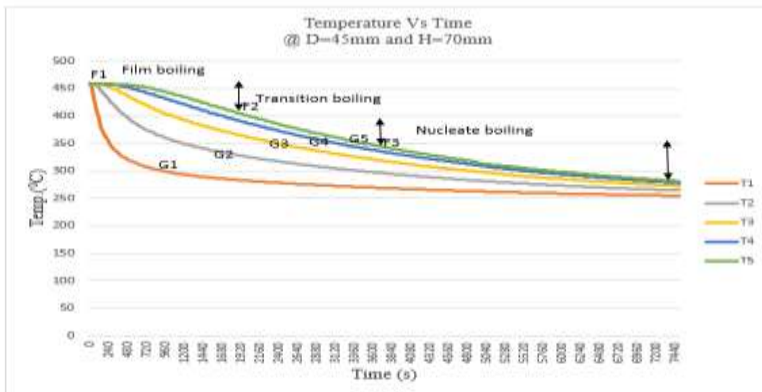

Fig.7: Temperature-time cooling profile for D=45mm and impingement gap H=70mm

4.0 Conclusion

The temperature profile of impingement cooling nearly show the same cooling mode from the film boiling to nucleate boiling, from cooling surface temperature range of 438°C to 500°C, and cooled linearly from 300°C to 260°C by finite temperature profile across the workpiece. The cooling rates at the film boiling modes are: 7.32°C/sec at D= 20mm and H=40mm, 11.25°C/sec at D =20mm and H = 70mm, 10.40°C/sec at D= 45mm and H= 40mm, and 5.65°C/sec at D 45mm and H =70mm respectively. Moreover, the values of cooling rates at the nucleate boling regimes are; 32.23°C/sec at D= 20mm and H=40mm, 36.31°C/sec at D =20mm and H = 70mm, 34.48°C/sec at D= 45mm and H= 70mm, and 32.26°C/sec at D 45mm and H =70mm respectively. Finally temperature profile of impingement cooling showed that the higher rates of cooling 11.25°C/sec under film boling occurred at smaller diameter, D, of 20mm and impingement gap, H, of 70mm. Howerver, the rate of cooling under nucleate boiling was 36.31°C/sec at diameter, D, of 20mm and impingement gap, H , of 70mm. Based on these results obtained, the rate of cooling is better achieved with smaller jet pipe diameters, D, and longer impingement gap,H.

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