American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-7, Issue-6, pp-304-310
www.ajer.org
Research Paper Open Access

Evaluation of Temperature Profile on Pool Boiling Using Jet Impingement Cooling System

T. O. Onah[a], A. M. Nwankwo[b] and J.N. Ani[c]

[a] *Department of Mechanical and Production Engineering, Enugu State University of Science and Technology Enugu, Nigeria.*
[b] *Department of Mechanical Engineering, Caritas University Amorji-Nike Enugu Nigeria.*
[c] *Department of Mechanical and Production Engineering, Enugu State University of Science and Technology Enugu, Nigeria.*
Corresponding Author: T. O. Onah

ABSTRACT: *Controlled accelerated cooling of pipe planar jets is commonly used in run-out-table cooling in hot rolling mills. 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.In this process astationary hot steel plate is studied by pool boiling mechanism .The cooling was achieved by pipe water planar diameters of 20mm and 45mm by impingementwater jets of 30 number holes and impingement gaps of 40mm and 70mm. The cooling rate 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 469^{0}C to 438^{0}C and500^{0}C to 458^{0}C, at high temperatures above the boiling point of water .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^{o}C to 500^{o}C, and cooled linearly from 300^{o}C to 260^{o}C by finite temperature profile across the workpiece.The cooling rates at the film boiling modes are : 7.32^{0}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. This agrees with 0 to 19.2 ^{o}C/sec in film boling ranges, mentioned in the literature by Lubb et al.,(2011) and Akmal et al., (2015). 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. This also agrees with ranges 30 ^{o}C to 45^{o}C mentioned by Akmal et al., (2015), in the nucleate boling regime. Finally temperature profile of impingement cooling showed that the higher rates of cooling 11.25^{o}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^{o}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.*

KEYWORDS: *Run-out table, impingement cooling, planar jet, impimgement gaps , pipe diamters, temperatures profile , pool boiling, film boiling and nucleate boiling.*

Date of Submission: 11-06-2018 Date of acceptance: 26-06-2018

I. INTRODUCTION

Run-out-table (ROT) cooling system in hot rolling mills is one of the key components of the thermomechanical control process, M. Mitsutsuka and K. Fukuda (2011). In ROT coolingsystem , the desired material structures are manufactured by the rapid cooling of hot steel plates from approximately 900°C to a predetermined coiling temperature using water jet impingement. Fig. 1 shows a schematic of the temperature profile of a hot steel plate during water jet cooling.N. Hatt*et al.*, (1993). Initially, 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.

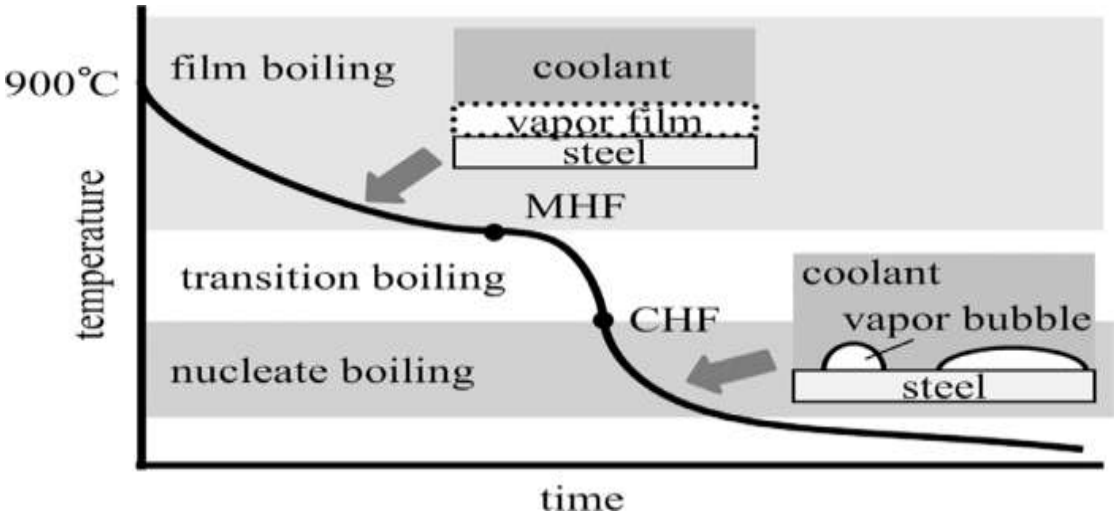

Fig. 1: Schematic of cooling curve of hot steel by water jet impingement. M. Mitsutsuka and K. Fukuda (2011).

In run –out table cooling system, when the coiling 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 to satisfy engineering demands. Many experimental works have been undertaken concerning the boiling heat transfer involving impinging water jets, D. H. Wolf, F., *et al.*, (2003) and J. Hammad, *et al.*, (2014) . Many of these studies were conducted considering single-jet impingement onto a stationary or moving hot solid . However, in actual ROT cooling, pipe planar array jets impact onto a stationary hot steel plate. 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.Some studies have analyzed single-jet impingement onto a stationary hot steel plate by S. Chen, *et al.*, (2001), M. Gradeck, *et al.*, (2009) and (2001).

In adition, Ishigai *et al.*,(1997), Sakhuja *et al.*, (2001), Monde *et al.*, (2002), and Haraguchi and Hariki (2006), examined multiple pipe laminar jets impinging onto a stationary hot steel plate. Recently, Vakili and GadalaS., Vakiliand M. S. Gadala (2013), investigated 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.

The objective of the present study is to investigate the temperature profile of pool boiling 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. Two pipe diameters of 20mm and 45nn, and impingement gaps of 45mm and 70mmof identical jets were arranged in a line in the width direction of the stationary plate.The spacing between jets and the temperature of the hot plate were considered as the main parameters and were systematically varied. The initial or surfacetemperatures of the hot plates were varied from 438^{0}C to 500^{0}C.

In the experiments, the flow structure of the coolant was observed flow meter measuring instrument and the temperature profile of the hot plate was measured bythermocouple in the control panel. 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.

II. MATERIALS AND METHODOLOGY

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

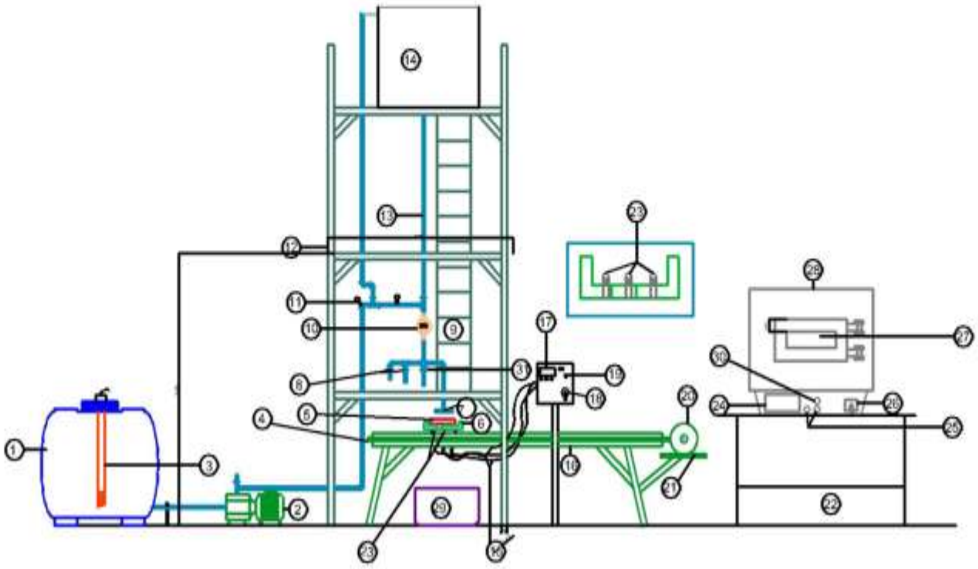

Fig. 2: Schematic of experimental apparatus.

KEYS:
1. Water tank2. Electric pump3.Heater4. Conveyor screw5. Work piece6. Work piece bed7. Impingement nozzle8.Ball gauge socket9.Ladder10.Flow meter11.Pressure meter12.Tower13. PVC pipe14. Reservoir15. Thermocouple wire16. Motorized Screw conveyor17. Thermocouple control panel18. Regulator19. Lock20. Electric motor21. Electric motor support and 22. Furnace support

The facility has been designed to simulate industrial cooling condition for run-out table cooling of stationary plates in hot strip and plate mills (Prodanovic*et al.*, 2004). It enables heat transfer to be studied during cooling of stationary plates. In this study heating was provided by an electric furnace where a steel plate was heated up to a temperature of 920^{0}C in MMEL using a motorized ASYNCHRONE ROTOR gear powered conveyor drive system of 0.75kw of 1500rpm to operate a gear of 1:24 by ratio with 50HZ under an ac. of 240volts, the steel plates were transported from the furnace to the cooling tower for the stationary experiments.
The cooling system features a closed water loop where 0.945m^3 (945 liters) of water was circulated throughout the experiment through the cooling jet nozzles. Surface temperatures, water temperatures, impingement heights or nozzle–to- surface spacing (impingement height) and flow rates were controlled. An ATLAS (ATP 60) water pump that provided total water flow rates of 60L/min was employed. It pumped water to the impingement plate from the water tank below to the target plate through the flow meter, nozzle header via impingement jet nozzle to the hot plate. An electric heater of 9kw of 330volts was situated in the tank and 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.

In this study, one type of nozzle was used; planar (water or curtain) nozzle. The cross section is 12x 12 mm of 30 × 90mm with 0.8 mm with 30 number holes of jet diameter.
A control panel mounted on a stand was used to read the surface temperatures of steel before and after the impingement. It has a red icons buttons that controls and records the temperature variations with digital read out on a steel cased panel.

2.1 Discretization of temperature development across the thickness

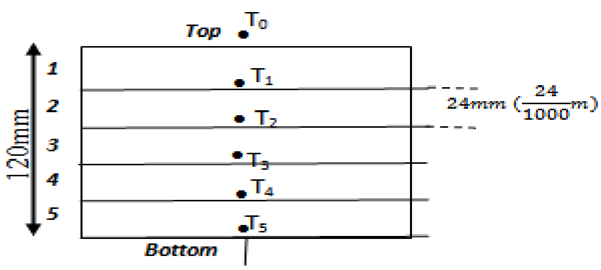

Fig.3: Sketch of temperature profile across the thickness from top to bottom plate

For the 1 –D"EXPLICIT F.D" to converge to a good solution; the stability is based on the conditions that { $0<\lambda\leq½$**}** (Crank, J., 2015)
If α = thermal diffusivity of steel
= 1.775×10^{-6} m^2/s
For $\Delta x = 24/1000$, and
$\Delta t = 30$ sec for the interval of each time used,
Solving for λ in the equation (6.2) of

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

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

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

The condition for convergence therefore becomes $\{0 < 0.092 \leq 1/2\}$
Thus, equation (6.2) becomes

$$T_{i,\,n+1} = 0.092T_{i+I,n} + 0.816\, T_{i,n} + 0.092\, T_{i-1,n} \qquad (2)$$

III. RESULTS AND DISCUSSION

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

Fig.4shows 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^{0}C at high temperature above the boiling point of water and falls below 300^{0}C, (Dhir 2014 and Wolf *et al*., 2013) . The boiling mode flow rates of 11.25^{0}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^{0}C/sec then shifts to strong nucleate boiling where numerous vapour bubbles are generated at the liquid –vapour interface instead of the vapour film.

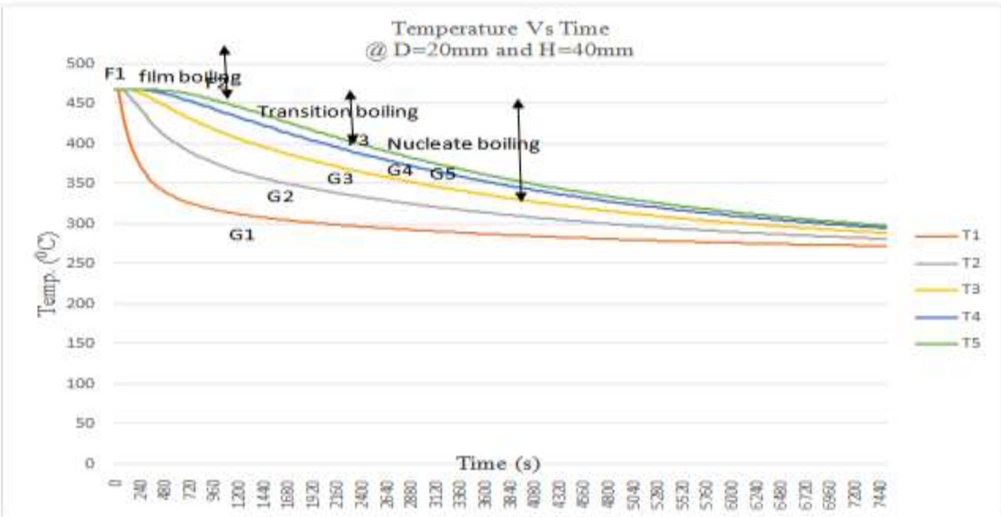

Fig.6.4: Temperature-time cooling profile on run - out table for D= 20mm and H=40mm

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^{0}C at high temperature above the boiling point of water and falls below 300^{0}C, (Dhir 2014and Wolf *et al*., 2013) . The boiling mode flow rates of 11.25^{0}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^{0}C/sec then shifts to strong nucleate boiling where numerous vapour bubbles are generated at the liquid –vapour interface instead of the vapour film

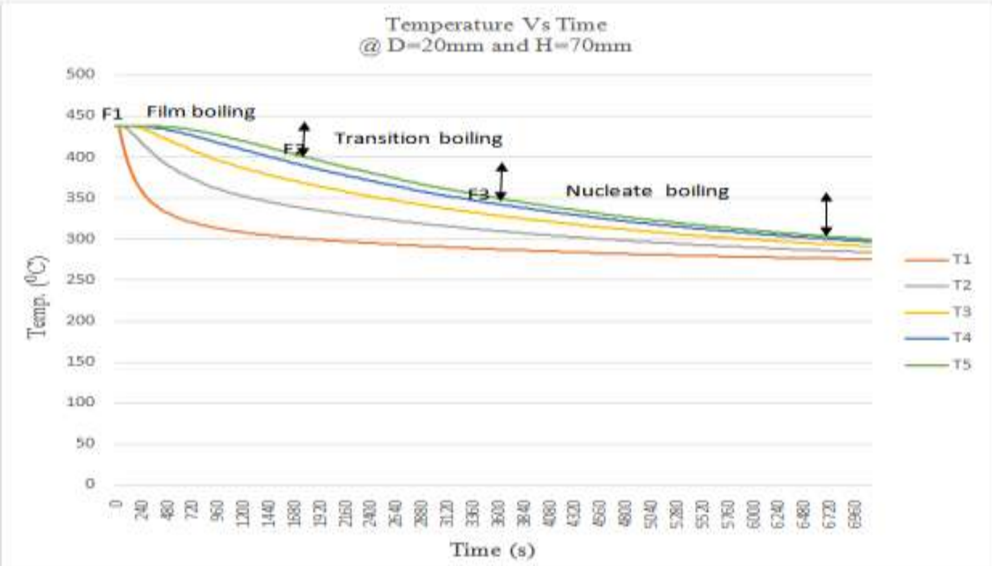

Fig.5: Temperature-time cooling profile on run - out table for D= 20mm and H=70mm

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 500^0C at high temperature above the boiling point of water and falls below 300^0C, (Dhir 2014and Wolf *et al*., 2013) . Here, the flow rates of 10.40^0C/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.

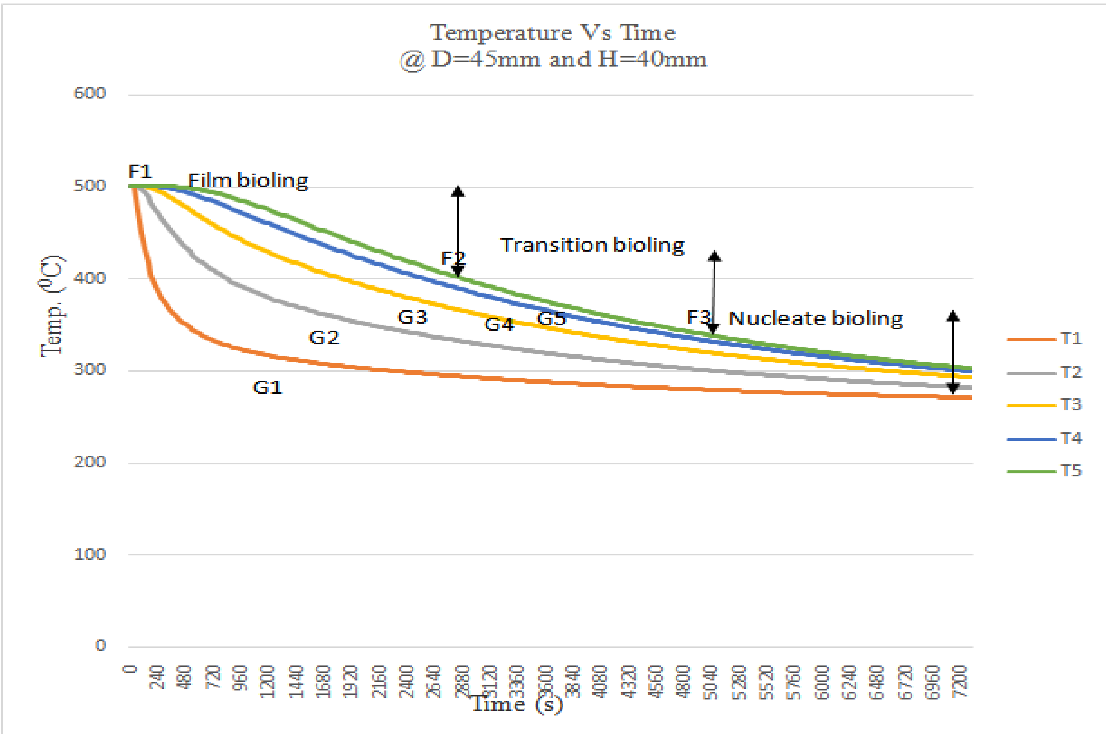

Fig.6: Temperature-time cooling profile on run - out table for D= 45mm and H=40mm

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 458^0C at high temperature above the boiling point of water and falls below 300^0C, (Dhir2014 and Wolf *et al.*, 2013) . The flow rate of 5.65 ^{0}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 32.26^0C/sce soon shifts to strong nucleate boiling where numerous vapour bubbles are generated at the liquid – vapour interface instead of the vapour film.

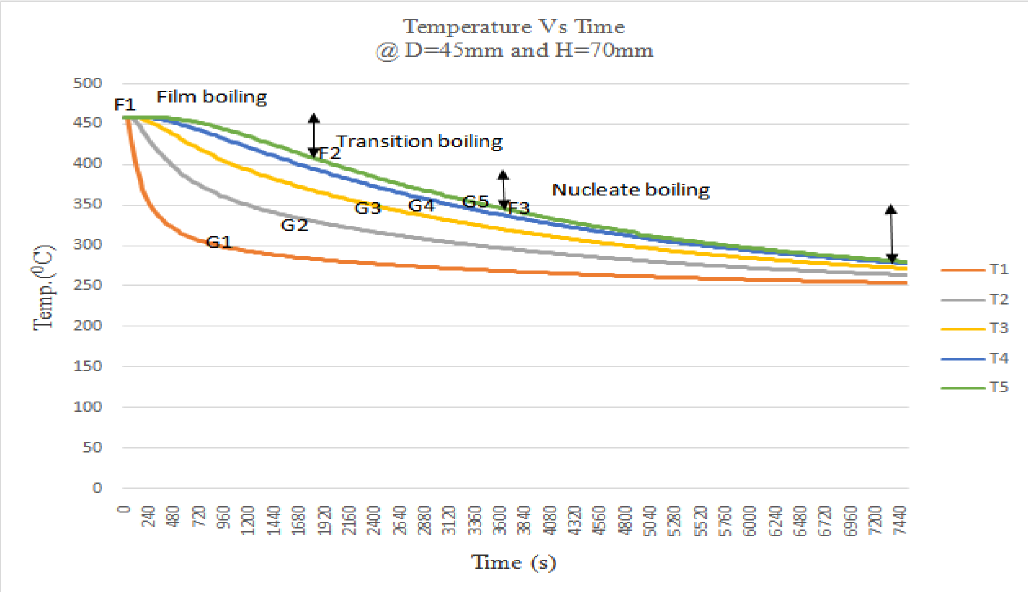

Fig.7: Temperature-time cooling profile forD=45mm and impingement gap H=70mm

IV. 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^oC to 500^oC, and cooled linearly from 300^oC to 260^oC by finite temperature profile across the workpiece.The cooling rates at the film boiling modes are : 7.32^0C/sec at D= 20mm and H=40mm, 11.25^oC/sec at D =20mm and H = 70mm, 10.40^oC/sec at D= 45mm and H= 40mm, and 5.65^oC/sec at D 45mm and H =70mm respectively. This agrees with 0 to 19.2 ^{o}C/sec in film boling ranges, mentioned in the literature by Lubb *et al.,(*2011) and Akmal *et al.*, (2015).

Moreover, the values of cooling rates at the nucleate boling regimes are; 32.23^oC/sec at D= 20mm and H=40mm, 36.31^oC/sec at D =20mm and H = 70mm, 34.48^oC/sec at D= 45mm and H= 70mm, and 32.26^oC/sec at D 45mm and H =70mm respectively. This also agrees with ranges 30 ^{o}C to 45^oC mentioned by Akmal *et al.*, (2015), in the nucleate boling regime.

Finally temperature profile of impingement cooling showed that the higher rates of cooling 11.25^oC/sec under film boling occurred at smaller diameter, D, of 20mm and impingement gap, H, of 70mm. However, the rate of cooling under nucleate boiling was 36.31^oC/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.

REFERENCES

[1]. Akmal M.A., M.T. Omar and M.S. HAMED (2015). An Experimental Investigation of Propagation of Wetting front on a Curved Surface exposed to an Impinging Water Jet. International Journal of Microstructure and Materials Properties, 3(415),654.681.
[2]. D. H. Wolf, F. P. Incroperaand R. Viskanta (2003),: Adv. Heat Transrf., 23- 31
[3]. Dhir, V.K. (1998).“Boiling heat transfer”, Annual Review of Fluid Mechanics,30: 365-401.
[4]. H. Fujimoto, K. Tatebe, T. Hama and H. Takuda (2014),: ISIJ Int., 1338:54 -65
[5]. H. Fujimoto, Y. Shiramasa, K. Morisawa, T. Hama and H. Takuda (2015): ISIJ Int., 55-64
[6]. J. Hammad, M. Monde and Y. Mitsutake (2014),: Therm. Sci. Eng., 12-19.
[7]. Lubb,Gradeck,Brian G. Thomas (2011).Numerical Study of Impingement Water Jets in Run-out Table Cooling Processes.
[8]. M. Mitsutsukaand K. Fukuda (2011), : Tetsu-to-Hagané, 11, 54-65

[9]. M. Gradeck, A. Kouachi, M. Lebouche, F. Volle, D. Mailletand J. L. Borean (2009): Int. J. Heat Mass Transf., 52, 1094.
[10]. M. Gradeck, A. Kouachi, J.L. Borean, P. Gardinand M. Lebouche (2011) . Int. J Heat Mass Transf., 54 - 57.
[11]. M. Monde, H. Kusudaand H. Uehara (2002: Heat Transf. Jpn. Res., 9 -18
[12]. N. Hatta, J. Kokadoand K. Hanasaki (1993): Trans. Iron Steel Inst. Jpn., 23, 50-59.
[13]. Prodanovic, V., Fraser, D., and Mihtzer, M. (2004). Simulation of Run-out Table Cooling by Water Jet Impingement on Stationary Plates – A novel experimental Method, 2nd International Conference on Thermochemical processing of Steel Ed. M. Lamberights, Liege, Belgium, 25-320.
[14]. Sakhuja, F. Lazgin and M. Oven (2001). ASME Paper 80-HT-47, ASME, New York47.
[15]. S. Chen, J. Kothari and A. Tseng(2001) . Exp. Therm. Fluid Sci., 4 343.
[16]. S. Ishigai, S.Nakanishi, M. Mizuno and T.Imamura (1997). Bull. Jpn. Soc. Mech. Eng., 20 , 85.
[17]. S. Vakiliand M. S. Gadala (2013),: Heat Transf. Eng., 34 -58.
[18]. Wolf, D. H., Incropera, F. P., Viskanta, R. (1993). Advances in Heat Transfer, 23:1-131.
[19]. Y. Haraguchiand M. Hariki (2006), : 2nd Int. Conf. on Modelling of Metal Rolling Processes, ed. by J. H. Beynon, Institute of Materials, London, 606.

T. O. Onah." Evaluation of Temperature Profile on Pool Boiling Using Jet Impingement Cooling System." American Journal of Engineering Research (AJER), vol. 7, no. 06, 2018, pp. 304-310.