Development of A Mechanical Setup With Sensors to Determine Interfacial Phenomena Between Supersonic Steam Jet and Water

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Abstract

A specially configured mechanical setup with sensors which was designed to record minimal and increased fluctuations in temperature as evidence of Kelvin–Helmholtz (KH) instabilities by means of LM35 sensors and data acquisition. The generation and spread of KH instabilities in steam and water was accomplished first time by following temperature profiles around the steam's jet interface with the surrounding water. The supersonic steam was driven into the water in a vessel by means of a specially designed supersonic nozzle at pressure changing from 1.5 to 3.0 bars. Whereas, the temperature of the water in the cylindrical column varied from 30 °C to 60 °C with a change of 5 °C each time when the measurements were performed. The acquisition setup was able to record temperatures across the steam jet in the vessel at a rate of 1 ms, and it could also provide the temperature readings within the vessel. Axial and radial temperature profiles being obtained from 6 temperature sensors positioned along the steam jet, revealed the instabilities being occurred across the interface among the steam and the water, the instabilities spread along the axis towards the vessel wall. However, these instabilities were influenced considerably due to the variation in water temperature in the column, along with change in steam's pressure. Also, instabilities were affected as well due to the change in viscosity of water owing to change in its temperature.

1. Introduction

Direct Contact Condensation (DCC) may also occur by injecting supersonic steam into the subcooled water. Due to the complex interfacial operations across steam and water, it is difficult to compute mass, momentum and heat transfer in DCC phenomena. Due to the significance of DCC in several commercial processes, such as steam jet ejectors, direct feed heated pumps, nuclear reactors (e.g. PWRs, BWRs) and others, there has been a lot of interest on the topic for over two decades. Hughes & Duffey, (1991) [1] studied momentum transfer with the separated flows involving DCC. This investigation emphasised the dissipation of turbulent energy due to the wall shear as well as interfacial shear. Their theoretical work reiterated Kolmogorov dissipation velocity and length scale related to the DCC phenomenon. Application of this scale on to the theory of turbulent eddy associated surface renewal provided accurate predictions for the horizontally injected steam condensation.

Theoretical investigation on instabilities [2], [3] along with the analysis were derived mainly through integration of conservation equations Yun, Qiu, Su, & Jia, (2008) [4]; Zhang, Su, Yang, & Qiu, (2009) [5], through the application of numerical techniques (i.e. finite volumes, elements or differences). Pan and Hanratty, (2002)[6] determined a relation for vertical gas-liquid annular flows, which was based on the balance between the atomisation rate of the wall liquid layer and the deposition rate of the drops on to the wall, where both rates decreased with increasing liquid rate. Thus, a relation was developed from theory, which related the particle (or drop, bubble) deposition constant to the turbulence caused by the particle. Gale, Tiselj, & Parzer, (2004) [7] studied the surface driven instabilities which were believed like KH instabilities associated to the production of water hammer due to the condensation, which was simulated by Il'ichev & Tsypkin, (2005) [8]. They found four mechanisms owing to the generation of

instabilities from the transformation interface in geothermal systems. Whereas, Strubelj & Tiselj, (2006) [9] worked experimentally at nuclear PMK-2 by emphasising on the condensation driven water hammer through direct contact condensation. The disagreement was found between the measurements with simulation results, the difference between the two was probably because of the erroneous wire mesh sensor that was used to determine turbulence related to the water hammer. Also, the major reasons, found to be accountable were inflow water's turbulence and choice of turbulence formulation, for the disagreement between the experimental and computational results. Guo, Huang, Xia, & Zeng, (2010) [10] reported the characteristics of instabilities, which were occurred in a twin channel having two-phase flow. They associated the parameters such as pressure and irregular heating conditions with the instabilities. Colombo, Papini, Cammi, & Ricotti, (2011) [11] addressed the influence of the instabilities occurring in DCC phenomenon on the fatigue life of the steam generator tubes. Shah et al., (2010) [12] depicted the interfacial area, associated with the emergence and propagation of instabilities, as a region with zero thickness in establishing the DCC model. They indicated towards the occurrence of the transformation of mass, momentum and heat through the thin line. No experimental or numerical evidence was found from the literature review presented here that indicates the generation and propagation of hydrodynamic instabilities of the interface, made of the supersonic steam's jet and the water. An effort was made here to develop a temperature sensor setup that can determine the evidence of hydrodynamic instabilities across the interface using the temperature profiles.

2. Experimental Setup

The experimental setup can be divided into the following categories.

Mechanical Setup:

A transparent cylindrical column (H: 610 mm, ID: 330 mm) made of Perspex, as seen in Figure. 1, was used to characterise the behaviour of interface among the supersonic steam and the water by capturing the changes in temperature within the steam jet. Two inflow ports are located at the bottom of the vessel to serve injection of water into it, and one outflow port is positioned at 475 mm from the bottom, at the circular wall of the vessel, to maintain the required level in the column. The exceptional aspect of the experimental facility is the development of the electro-mechanical method for temperature measurement of the steam jet. As seen in Figure. 1, temperature measuring setup comprises a central upright plastic square duct having six horizontal hoses connected to the bottom of the central duct. The pipes are assembled over a plane and placed at the same angular gap among them. Inside of each of these tubes contains a protruded surface along its complete distance to permit the tube containing the temperature sensor to move between its two edges as illustrated in Figure. 2.

Whereas, a SS pipe was inserted into the central duct, which had threads with a pitch of 1 mm, made on its inner surface. A SS bar with threads, was screwed into the SS pipe and with the help of two micro-controlled motors, clockwise and anticlockwise revolution of the SS bar along with vertically upward and downward movement of the duct were maintained, details in this regard can be seen in Figure. 3. The

function of one of the two motors linked to the circular clamp, as seen in Figure. 3 (a), was to facilitate movement along up and down of the square duct. The six temperature sensors were attached to the rod through the central duct by means of wires.

However, bringing the six temperature sensor tubes towards the centre of the vessel was initiated by causing movement of the SS rod through producing tension in the wire attached to the tubes containing temperature sensors, which will cause these tubes to guide towards the square bar. Whereas, with the SS bar being rotated down may cause the temperature sensor tubes to displace away from the centre because of the springs to cause restoring action. Function of a circular clamp as shown in Figure 3 (a) and (c) was to allow the sensors to climb up and down along with rotating across the horizontal plane. This setup has been useful to assist the six temperature sensors to record temperature at any location over a horizontal plane because the three rods could be joined to the central clamp of square metallic, which facilitates rotation over the metallic ring as shown in Figure 3 (a) and (c).

Temperature Controlling System (TCS)

Temperature of the subcooled water in the column was checked with three temperature sensors placed at the top, middle and bottom of the column's wall, which was part of a micro-controller based TCS. The water temperature in the column was retained at a required value (i.e. 30°C to 60°C) through injection of freshwater by two inflow ports placed at the bottom of the column on instruction by the feedback of the TCS. There was a problem with TCS functioning as expected from the system. The reason behind the erroneous function of the TCS was due to its being located in the huge gap between the vessel size and the steam's jet size. The estimated diameter of the steam jet at steam's pressure of 3 bars, was only 5 mm. Whereas, the mass flow rate associated to the much smaller steam jet diameter, was only approximated as ~ 4 g/sec, however, when the mass of the water in vessel i.e. ~ 52 Litres, was compared with the little steam mass, it can be judged that the water temperature couldn't raise in the given time to a value that could trigger TCS. Secondly, it was noted that the TCS functioned only for a duration of 10-15s after an average time of about 5-6 min. Since. The temperature corresponding to the water neighbouring the steam's jet may rise because of the persistent condensation, so this rise in temperature should be uniform as observed in the beginning of each profile nearby to the interface of the jet, which was contrary to what being noted at the supersonic steam's exit from the nozzle. The temperature profiles were seemed continuous initially, however, afterwards they became uneven, which may be ascribed to the instabilities generated at the interface.

Acquisition of Temperature Data

The Data Acquisition (DAQ) can acquire 1000 readings in a second. Among the two motors involved in the acquisition setup, one was used to revolve the rod with one revolution in a span of 20 s. Since, the pitch of the threads being engraved around the rod was about 1 mm, which corresponded that three full rotations of the rod covered a linear distance of about 3 mm in a minute, when undertaking measurements of the radial temperature. However, the pitch of the threads in case of applying the second

motor was 20 mm and a duration of 20 seconds was needed to complete a revolution, so a height of about 60 mm was traversed in 1 min, when undertaking the axial temperature measurements. Both motors could cause motion with a deficiency of 6%. Keeping in view of the elevated data rate as well as having replication of temperature measurements at any position and sensor's time constant, nearly 500 temperature readings were expected along a mm of length. LM35, as being the precision integrated-circuit temperature sensors, was used to measure the temperature of the water, steam jet and the steam-water interface, which was found as a direct measure of the output voltage. They were calibrated in an Oven, which covered the temperature range, 0°C – 300°C, with an error of $\pm 0.2^\circ\text{C}$. Whereas, each sensor was able to provide the averaged reading in mV corresponding to a rise of 1°C was 9-10 mV/°C, and the error in temperature measurement corresponding to each of the sensor was within $\pm 0.8^\circ\text{C}$. With time constant being in the range of 2~5 ms for each sensor, the sample rate of 1K/sec was chosen corresponding to each temperature measurement for a recording duration of 2 min and having five repetitions to determine the mean value. The authenticity of the measured data was tested on statistical assessments, and it was found that the data sets had a confidence interval of more than 90%. Also, as seen in Figure. 4, the front face of the LM35 sensors could only sense the temperature. Thus, while they were traversed across the jet, the likelihood of fluctuations in temperature owing to the disturbances in the flow might be substantial if the sensor could sense the temperature through its side faces (see Figure. 3(d)).

Since, the disturbance in the flow occurred a great deal at the side faces of the sensor than its front face, which was at 0° or parallel to the mass flux lines of vertical steam injections, therefore, no steam's mass flux lines striking the front face of the LM35 sensor, this confirms that a very little possibility existed, owing to the temperature measurements being disturbed due to the flow disturbances across the sensors. Also, even having minimal flow fluctuations taking place at the front face of LM35 sensors, and in an instance, when all the sensors were moved off the edge of the jet to its centre line, any error thus originated will be expected equally into the measurements recorded by each of the sensors. Further, the dimensions of the sensors (d:l:w=4:4.32:3.43 mm, Instruments, 1999) [13] were less than the size of the most swollen part of the jet (i.e. > 5 mm) thus, the probability of flow fluctuation because of the physical dimensions of the sensor was small. However, all six sensors used for the temperature measurements provided a linear response to the real temperature of the water.

The measurement of axial temperature was initiated by bringing the sensors to join at the middle axis of the jet, as seen in Figure. 4, at this instant, the DAQ was turned ON. The sensors were moved from the jet's tip to the nozzle exit; at this instant, the DAQ was switched OFF. The set was repeated to obtain steam jet's temperature profiles against each temperature of the water in the column, 30°C to 60°C with 5°C increment at steam's pressure ranging from 1.5 -3 bars. Whereas, the layout used to measure radial temperature across the jet's interface can be seen in Figure. 4. The sensors were first brought near to the widest section of the steam jet, which was slightly below the mid of the jet's height. The nozzle features and operating parameters along with their corresponding ranges, are summarised in Table 1.

Table 1
Operating Parameter and their Ranges.

Parameter (unit)	Range	Increment	No of Data Sets
Pressure (bar)	1.5–3.0	0.5	04
Temperature (°C)	30–60	5	07
Time constant of LM35 (ms)	2–5	-	-
Calibration Factor of LM35 (mV/ °C)	9–10	-	-
Data acquisition rate (samples/s)	1000	-	-
Nozzle inlet (mm)	20	-	-
Nozzle throat (mm)	2	-	-
Nozzle exit (mm)	3	-	-

3. Results & Discussion

In the current study, the evidence of the generation of hydrodynamic instabilities as well as their propagation was found by recording temperature profiles across the steam jet using the device developed as shown above. This was achieved by determining the influence of steam's inlet pressure and temperature of water in the vessel on the temperature variation on axial profiles and radial profiles obtained across the steam's jet.

3.1 Axial Temperature Profiles

As stated above nearly 60,000 temperature readings were obtained along the vertical axis of the steam jet to look at the generation of hydrodynamic instabilities and their influence on the interface involving supersonic steam jet and the surrounding water.

Influence of Water Temperature & Steam Inlet Pressure: Axial temperature measurements presented in Figure 5 were obtained with the steam's inlet pressure varying within 1.5 – 3.0 bars, whereas, the temperature of the water in the tank ranged from 30°C to 60°C. The temperature profile obtained at 30°C shows that the temperature reduces along the axis, however, in the region close to the nozzle's exit, the profile reveals independence from the temperature of the surrounding water [14], [15], [16], [17]. When the water temperature in the column increased, the nature of the temperature profile along the axis developed highly fluctuating. This was possibly due to the overturning motions being formed at the interface that involved entrapping water from the region in the neighbourhood of the interface [18]. Further, at low water temperature in the vessel, the condensation rate is higher, which causes the minimal instabilities across the steam-water interface because of the sub-cooling. Higher condensation rate provides a calming function to reduce the instabilities at the interface. Another interesting outcome from the Figure. 5 is that with increase in the steam inlet pressure, axial temperature profile seems more continuous at low

temperature of the water in the column, which reveals the importance of the influence of temperature of water in the vessel on the variations of temperature within the steam jet.

At a higher temperature of the water in the column, the axial temperature profiles showed strong fluctuations [14][17] particularly when the temperature of water raised from 45°C to 60°C. Such observations were evident due to the higher steam jet's velocity than the water in its surroundings that generated KH instabilities across the interface. Due to an increase in steam pressure, an increase in the amplitude owing to the fluctuations in temperature was observed, which hinted to an increase in the growth of these instabilities at the interface, thus resulting in an increased entrapment of water (i.e. ~20 - 30 mm). Therefore, with an increase in steam's inlet pressure and water temperature in the vessel, the penetration length and the width of the jet also increased that has been in accordance to the earlier measurements [14-15,19-20]. Since, an under disbursed nozzle [15] was used for steam injection here. Thus, the pressure at the nozzle's exit should be larger than the pressure being exerted backwards. In accordance with the compressible flow theory [21] an expansion wave occurs for the present case at the nozzle's exit because of the pressure difference between the nozzle's exit and backpressure. With an increase in steam's inlet pressure, the nozzle steam rate increases, along with an increase in exit pressure and Mach number. Increase in pressure at the nozzle's exit also raises, it's gap over the backpressure, which triggers the steam jet to expand explosively, this results towards a reduced pressure as well as the temperature, outside of the nozzle's exit, which can be seen in the temperature profiles in the Figure. 5.

Occurrence of hydrodynamic instabilities due to unstable interface:

With the help of Figure. 5 an attempt is made here to determine the effect of pressure of steam injection and change in temperature of the surrounding water in a column on the interface between the steam and water. Here, the reasons have been elaborated relating to the existence of fluctuations in temperature obtained along the centerline of the steam jet, which is ascribed as the KH instabilities. Even such instabilities have appeared at steam's inlet pressure of 1.5 bars, signifying the velocity difference as the lowest possible between the steam and the water. The instabilities propagate along axial centreline. The temperature profiles, found at steam's pressure of 1.5 bars against a range of water's temperature in the column, particularly temperature greater than 45°C, are shown in a magnified view in Figure 6. It is apparent from the Figure that when the temperature of water in the column raises with even maintaining the inlet pressure constant, the jet becomes unsteady [20,22] as evident from the very fluctuating temperature profiles as exhibited by the regions 1, 2 and 3 corresponding to the higher water temperatures of 50, 55 and 60°C respectively in the vessel.

Whilst steering the sensors from the front of the jet to the nozzle's exit along the centerline, it was found, at first there were minimal variations in the temperature contours at nearly 50 mm farther from the nozzle's exit. Nearly all the temperature profiles show elevated fluctuations being emerged at a distance varying between 20 mm and 40 mm, which depended upon the temperature of water in the column. At higher sub-cooling, i.e. 30°C it was found that the fluctuations existed at a distance within the vicinity of the nozzle exit. Also, the amplitudes associated with the fluctuations appeared in case of water

temperature of 30°C were smaller than those obtained for temperatures higher than 45°C. The spontaneous appearance of fluctuations was mainly due to the high sub-cooling; in this case, the penetration distance of the jet was small. Thus, the surface area accessible for the heat transfer as well as mass transfer from steam to water was small as well. The fluctuations across the interface occurred owing to the gradient of velocities within this region, subsequently these fluctuations propagated to the centerline of the jet. Due to the increase in water temperature, the distance, where the fluctuations occurred, increased in addition to the increase in fluctuations' amplitude. Also, fluctuations shifted to the right, as seen in Figure. 6, exhibiting a dislocation of the interface away from the nozzle's exit to the water region. These fluctuations may be ascribed as condensation oscillation (CO) as reported by Arinobu, 1980 [23]; Aya & Nariai, 1991 [24]; Chun et al., 1996 [22]; Yan et al., 2010 [20] which occurred at low mass flux with rise in water temperature in the vessel, thus giving rise to the instability at the interface of the steam jet and water [25]. Formation of these fluctuations along the axial axis of the jet at the temperature of the water in the vessel greater than 45°C may contribute to increase the shear across the interface, which caused KH instabilities. It is well known that at elevated values of inlet pressure, the flow rates and the Mach number of the steam leaving the nozzle may increase, which may induce additional momentum into the water layers in the neighbourhood of steam jet, which may provide added intensity to the KH Instabilities. These instabilities consequently grew into eddies that acted to entrain the water by the steam at its interface [18], which gave rise to fluctuations that propagated towards the mid, along the centerline ($r=0$) of the jet. Moreover, in case of higher condensation interface between the steam and water. Here, the reasons have been elaborated relating to the existence of fluctuations in temperature obtained along the centerline of the steam jet, which are ascribed as the KH instabilities. Even such instabilities have appeared at steam's inlet pressure of 1.5 bars, signifying the velocity difference as the lowest possible between the steam and the water. The instabilities propagate along the axial centerline. The temperature profiles, found at steam's pressure of 1.5 bars against a range of water's temperature in the column, particularly temperature greater than 45°C, are shown in a magnified view in Figure 6. It is apparent from the Figure that when the temperature of water in the column raises with even maintaining the inlet pressure constant, the jet becomes unsteady [20,22] as evident from the very fluctuating temperature profiles as exhibited by the regions 1, 2 and 3 corresponding to the higher water temperatures of 50, 55 and 60°C respectively in the vessel.

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The temperature profiles illustrated in Figure 8 became more uninterrupted at 30°C due to the increase in steam inlet pressure, this indicates an inclination of the jet transforming towards stability which was referred by Chun et al., (1996) [22] as stable condensation. At elevated water's temperature in the column, the jet became fiercely unstable because, at elevated values for the temperature, the interface moved with larger velocity than the surrounding water, this resulted into the formation of KH instability at the interface. Moreover, the temperature profile in Figure 8, seems non-symmetric, the region within the centreline of the jet at a radial distance, $r = 0$, particularly when the temperature of the water in the column exceeds 45°C. It can also be seen in Figure 8, that the width of the jet has been raised with a rise in pressure, which supports work performed elsewhere [18][15][25][19]. The temperature profiles obtained at all pressures show peak temperature values at $r=0$, these values decrease to the ambient when the temperature sensors were moved away from the centre of the jet, which is found consistent with work reported by Song, Cho, & Kang, 2012 [26]; X.-Z. Wu, Yan, Li, et al., 2009 [15]; J. Yan et al., 2009 [17] for sonic and by X. Z. Wu et al., 2010 [16] by supersonic and on CFD basis by Davies, 1967[27]; Gulawani et al., 2006[18]; Xu et al., 2013[28] for steam jet. Since, the six sensors were not located at the same position on XYZ coordinates during recording temperatures, it is then worthwhile to disclose that the sensors may have recorded even the minor fluctuations in the temperature, which may have been generated transiently. However, these sensors were calibrated as being placed stationary and letting them in motion through water at temperatures varying from 30°C to 60°C, the sensors responded no departure from a linear response, thus, confirming the validity of measurements. It is useful to express here the earlier studies [24][17][16] [26][28], which were performed relating to the temperature measurement across the steam jet radially, the thermal sensors crossed one end of the jet on the horizontal axis to the other end of the jet. However, no study was performed supporting coordinated temperature measurement with six sensors located on a plane tending a fixed angle of 60° between each other to determine a temperature

distribution at a high sample rate as performed here. The method adopted here, can acquire the factual temperature profile at the same time along six different angular locations at an elevated speed, accuracy and spatial resolution can apprehend the indication of KH instabilities and their propagation associated to the injection of the supersonic steam into the subcooled water.

3.2 Radial observation of Hydrodynamic instabilities:

Capturing temperature fluctuations across the steam jet's interface with the surrounding water was mainly to find the sign of the presence of the Kelvin Helmholtz instabilities because of the change in velocities between the steam and the water. The instabilities were much short-lived. Thus the equipment specialised in highly spatially determined temperature measuring was utilised to capture them, as reflected in Figure. 9. The generation of these instabilities, along with their propagation across the interface, can be portrayed from the Figure. 9-10. The temperature profiles in Figure 10 were transformed with the help of scattered points in Figure. 8 & 9. However, when the scattered points were joined together, they did not convert to a solid line, rather small ridges and depressions indicating amplified fluctuations in the temperature profiles obtained for up to $r > 0.02$ m, as seen in area 1, 2, and 3 in Figure. 10. Such fluctuations were formed due to the velocity shear and buoyancy between steam and water. Whereas, the gravity normally acts to reduce the shear in the vertical flows. Thus, with lessened shear, the expectations of the formation of eddies are fewer. Because of the formation of a minimal number of eddies indicates the reduced ability of the steam's jet to entrain the surrounding water through the interface. Thus, reduced entrainment of water across the interface provides comparatively lessened generation of KH instabilities, which is evident from the increased fluctuations in temperature as seen in Figure. 9.

Additional contribution into the generation of KH instabilities associated with the fluctuations in temperatures at low sub-cooling of $45^{\circ}\text{C} - 60^{\circ}\text{C}$ can be because of the variation in water stream's dynamic viscosity at the interface with an increase of temperature of the water in the column. This can be described as followed: the surface tension of the water surrounding the steam jet decreases from 71.20×10^{-3} down to 66.24×10^{-3} N/m (e.g. [29]) as a rise in temperature of surrounding water occurs from 30°C to 60°C respectively, whereas corresponding to the same range in temperature, the dynamic viscosity decreases from 0.798×10^{-3} down to 0.467×10^{-3} N-s/m². So, a drop of about 6% in surface tension and 60% in viscosity occur with increase in temperature from 30°C to 60°C . Thus, the role of viscosity to damp the discontinuous propagation of the instabilities is effective at higher sub-cooling values. However, when the water temperature in the vessel goes up from 30°C to 60°C , the viscosity may reduce nearly half of the value, thus supporting more to the propagation of instabilities being observed across the steam-water interface. Another contribution into the high amplitude associated to the fluctuations in the temperature is due to the thermal and momentum exchange across the interface. When the sensors were steered to the nozzle exit, drop in the local density and viscosity of the water surrounding the steam's jet was occurred due to the higher temperature of the steam jet than the water. This in turn induced an increase in the upward axial flow velocity, which was smoothed by the thermal and

momentum exchange acting perpendicular to the axial flow of the steam's jet and this contributed towards a rise in abrupt temperature fluctuations [30].

A further significant from Figures. 9 and 10 is the asymmetric behaviour of the radial temperature distribution, which has become more apparent in their 3D profiles (Figures. 9 and 10). From these Figures, the asymmetric trend can be seen in two opposite directions, which was reported in many investigations [12,16, 28, 31-33] dealing with the flows of compressible fluids. The reason behind this trend could be associated to the high intensity of turbulence across the interface. Also, the asymmetric behaviour can not only be seen in the adjacent sensors (Figure. 10(a)) but is also true in case of opposite sensors (Figures. 8 and 1(b)).

Conclusion

For the first time an experimental evidence was presented of the generation of hydrodynamic instabilities for condensable fluids (i.e. steam and water) by use of temperature sensors. Supersonic steam was introduced into the sub-cooled water in a vessel, and the temperature measurements were made across the steam jet, using six LM35 digital sensors and PCI-6033 NI DAQ card. Axial and radial temperature profiles of the steam jet were measured by making use of a specially configured mechanical setup, which facilitated traversing of six sensors along axial and radial axis of the steam plume in the column. Temperature measurements were performed at different inlet pressures, with a temperature of water in the column was varied. Temperature profiles, thus obtained, revealed the existence of KH instabilities, which strongly depended on inlet pressure, water temperature as well as viscosity for their generation and propagation. The sub-cooling proved strongly as a damping factor for interfacial instabilities. Also, viscosity of the water surrounding the steam jet functioned to damp KH instabilities as well, and this mainly depended upon the level of sub-cooling.

Declarations

AVAILABILITY OF DATA AND MATERIALS

REPLY: The data files will be presented upon request for this research

COMPETING INTERESTS

REPLY:

DECLARATION REGARDING CONFLICT OF INTEREST

Respected Sir:

It is declared that the manuscript attached here has no conflict of interest.

Regards

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AUTHORS' CONTRIBUTIONS

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HELP IN MANAGEMENT OF THE PROJECT & PROCESSING OF DATA.

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Figures

Figure 1

A schematic of complete temperature acquisition setup.

Figure 2

A schematic of a section of horizontal rod section of the temperature acquisition.

Figure 3

(a) Height controlling clamp with horizontally rotating square clamp, (b) vertical rods at center, (c) complete system with input/output/GND wires, and (d) LM 35 sensor's dimensions.

(a)

(b)

Figure 4

(a) Axial measurement and (b) Radial measurement.

Figure 5

Axial temperature profiles of steam jet, (a) 1.5 bars, (b) 2.0 bars, (c) 2.5 bars, and (d) 3.0 bars.

Figure 6

Temperature fluctuations at 50, 55 and 60oC.

Figure 7

Radial temperature profile of steam jet, (a) 1.5 bars, (b) 2.0 bars, (c) 2.5 bars & (d) 3.0 bars.

Figure 8

Temperature fluctuations at different water temperatures.

Figure 9

3D Plot of radial temperature measurements.

Figure 10

Asymmetric temperature distribution.