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Hydrodynamics of Direct Contact Condensation Process in Desuperheaters

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ABSTRACT:

Due to the global warming and environmental implications, the focus of household heating has shifted from fossil fuels towards environmentally friendly and renewable sources. Desuperheaters have been found an attractive option as a domestic provision for the warm water; they used steam induced direct contact condensation (DCC) as the major means to warm the water. The present study has been an attempt to investigate the hydrodynamics in the Desuperheater vessel experimentally, when the pressurized pulsating steam was injected into the vessel, where, the steam jet interacted co-currently with the slow-moving water. Visual flow visualization provided an overall flow picture that showed a circulation region when the pulsating steam was injected into the slow co-currently moving water and the peaked vorticity corresponded to the steam injection duration varying from 10-60 seconds. An array of 7 Hot Film Anemometers (HFA) was traversed axially and radially to determine the velocity fluctuations at 0 – 20 cm from the steam's nozzle exit. Vortical structures were obtained that corresponded to the entrainment of the steam with the surrounding cocurrently moving water. The circulation regions were thus exhibited in relation to the steam's injection durations as well as the downstream axial distance of 2 cm and 15 cm from the nozzle exit, which showed that the core local circulation at 2 cm, lost 75-79% of its circulation at 15 cm downstream of the nozzle exit.

KEYWORDS

Steam-water flow; Hydrodynamics; Pulsating injection; Local and core circulation; Vortical Structure.

1. INTRODUCTION

The demand for energy on a domestic level has increased over the years, forming a greater proportion of total energy demand. Several factors are responsible for this rise, including, population growth, growing economy and thus wealthier lifestyles causing an increase in the use of electronic devices and vehicles. Another facet of the issue is the increasing usage of energy resources like fossil fuels. Such fuels have a definite age and quantity, but their increasing usage devastates the global outlook by polluting the environment. Thus, attention has diverted to renewable energy resources with increased efforts to determine renewable sources as a replacement of fossil fuels. Household warm water contributes to a major share in energy consumption. e.g. based on descending order; it consumes 32% in South Africa (Nkomo, 2016), 29% in Mexico (Rosas-Flores et al., 2011), 27% in China (Mahmoudi et al., 2018), 25% in Australia (GOVERNMENT, 2010), 22% in Canada (Aguilar et al., 2005), 14% in Europe (Trends, n.d.) and 11% in USA (Allouhi et al., 2015).

There are many systems which exist to provide customized solutions suited to a household's warm water requirement. These systems depend upon the climate, the nature of the requirement, nature of energy resource, and the design of the system. Thus, the selection of a suitable energy system could reduce the cost of warm water production and help save on unnecessary usage of energy resources, whilst being environmentally friendly. There are numerous studies (Chow, 2010; Hepbasli and Kalinci, 2009; Jaisankar et al., 2011; Shukla et al., 2009) on methods being used to provide warm water to the households which heat-pumps, solar water heaters with phase change materials, and thermal/photovoltaic solar technology-based systems. All these studies are comprehensive reviews,

within which the usage of the desuperheaters have been elaborated in detail. Desuperheaters performed a cordial role in the provision of the warm water, irrespective of the sources from where they inducted steam. They were involved in the processes such as the direct contact condensation that became the central to warm the water. Yet myriad times, the desuperheater setup has been discussed in depth. Still, till the date, there wasn't any study to our knowledge that discussed the issue of the direct contact condensation (DCC) induced hydrodynamics within the mixing region in the desuperheater including the pulsating steam injection. The current study is an effort in this regard. In the current study, a detailed analysis has been provided for the hydrodynamic trends prevailed in the desuperheaters. The present study focused on the effect of the short pulse high-pressure steam injection into the continuous very slowly flowing water, and thus, the overall effect of the pulse injection on the in-situ hydrodynamics was determined. The sequence of the events that occurred within the mixing chamber was characterized, and the flow structures like vorticities, right from the moment they came into being till the time they decayed, were described in detail. The details of the experimental setup and the sequence of performed experiments are given in the proceeding section.

2. EXPERIMENTAL SETUP

The experimental setup comprised of a desuperheater vessel, which is shown in Fig 1.

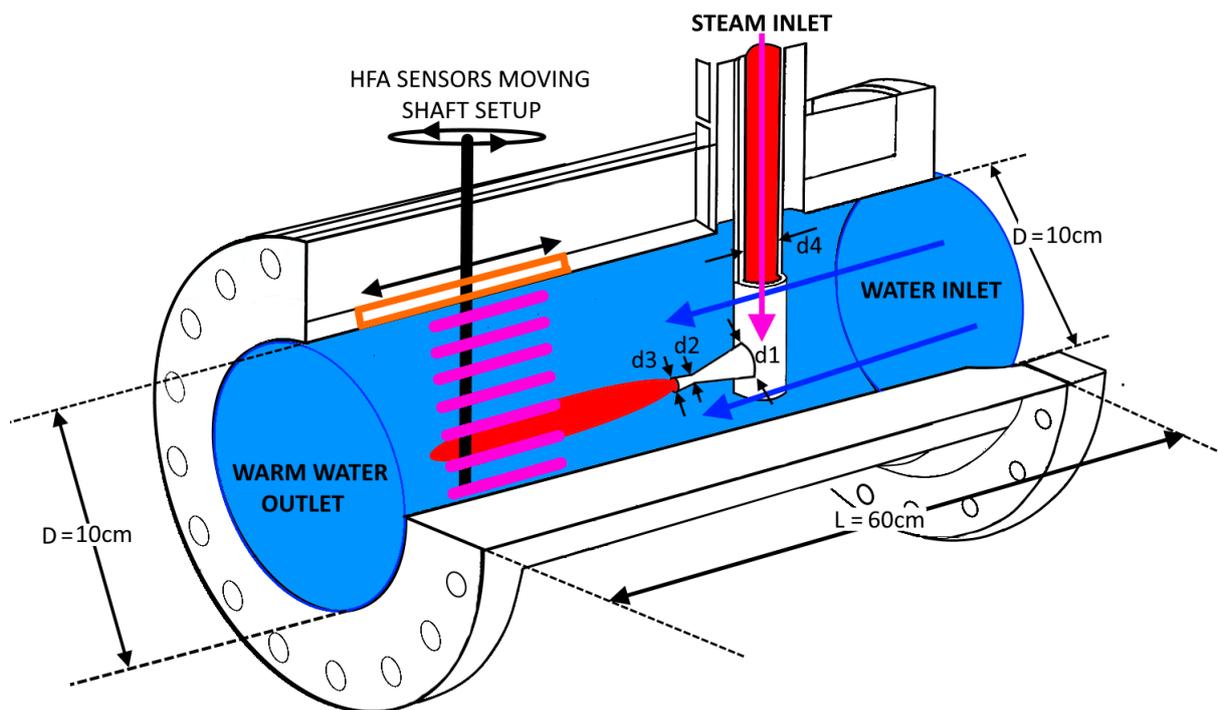


Figure 1. An experimental Setup (Desuperheating vessel)

The steam was injected into the desuperheater through a nozzle attached to a vertical duct. The vertical duct was submerged in the vessel, and the nozzle was located at the axial centre of the desuperheater's vessel. The inner diameter of the vertical duct is 3 cm, the inner diameter, d_1 of the nozzle is 2.5 cm, the throat diameter d_2 is 1 cm and exit diameter, d_3 is 1.5 cm. The length of the nozzle is 10 cm, and the diameter and length of the desuperheater vessel are 10 cm and 60 cm, respectively. The vessel was filled with subcooled water which moved with very lower velocity, 0.01cm/sec and the steam was

injected at the stable gauge pressure of 4 bars in pulsating mode. The steam's injection was controlled using a solenoid valve and an electronic control system (ECS) installed upon the main steam line (not shown) in Fig 1.

Hot Film Anemometers (HFA) were used to measure velocity fluctuations associated with interfacial steam-water flow. A fixture was made to facilitate forward and backward movement of the seven HFA within the fluid medium in the vessel. Before performing the experiments, the steam's mean velocity was measured at the exit of the nozzle by using the pitot tube. The dynamic pressure measured at the front of the pitot tube can provide the axial steam's mean velocity (V_s) at the location of the front face of the pitot tube, through the application of the Bernoulli's equation, expressed as,

$$V_s = \sqrt{\frac{2\Delta p}{\rho_s}} \quad (1)$$

where Δp is the pressure difference between total pressure at the mouth of the pitot and the static pressure and ρ_s is the steam density. This velocity was used to non-dimensionalize the velocity values obtained from the HFA sensors. The ECS could also monitor the movement of this fixture in clockwise and anti-clockwise directions to control the movement of the HFA sensors along the axial axis through initiating forward and backward movement of the HFA sensors. The velocity fluctuations were measured along the axial (X-U) and radial (Y-V) directions. All the seven HFA sensors were used at same time such that the array traversed a distance of 20 cm along the axial, from the downstream towards the upstream by acquiring the data for 1 min at a single location along the axis. Then it traversed forward to a distance of 1cm, and again the measurements have been done. in this way the whole medium comprised of the mixture of steam and water has been scanned in a vertical plane from a distance of 20cm till the exit of the nozzle. Both of these velocity values as a function of the spatial distances along which these have been recorded gives us useful information related to the total circulation along the axial direction, and local circulation and the velocity distributions along the radial direction. The total circulation (Linden, 1973) was measured with the help of the velocity fluctuation along the x-axis and the area containing the axial and radial velocity fluctuations being measured provided the total circulation, Γ of the vortical ring. Whereas, the local circulation in terms of the angular velocity distributions along the radial direction (Linden, 1973) was calculated by using the following relations,

$$\Gamma(x) = 2\pi r V(r) \quad (2)$$

$$\omega(r) = \frac{\partial V}{\partial x} - \frac{\partial U}{\partial r} \quad (3)$$

The experiments thus performed and the discussion on the acquired results has been presented in the following section.

3. RESULTS & DISCUSSION

In the current study, the steam was injected at 5 bars of gauge pressure into a desuperheating vessel in a pulsating mode. The flow hydrodynamics associated with the flow regimes evident in the vessel was investigated with special emphasis on the vortical structures and circulation flows generated within the concurrently slowly flowing water. The details of the accompanying results in this regard were given as follows.

3.1 Hydrodynamics of the flow regime, an overview

The overall inference drawn from the experiments performed, the flow domain exhibited a flow circulation profile each time when the steam was injected into the slow cocurrently moving water. Across the whole of the flow domain, the vorticity peaked at different injection time durations, that varied from 10 till 60 seconds. This vorticity weakened downstream of the steam's injection when the sharp shear between the steam and surrounding water at the point of injection, reduced in magnitude as the steam's jet spread across due to the surrounding water being entrained by the steam. However, the formation of large vortical structures due to the high-speed spontaneous injection of steam depended upon the time duration the steam was injected and the length across which the vorticity prevailed varied in accordance to the duration of steam's injection, and the Reynold number of the steam at the nozzle exit. The vortical structures thus formed, exhibited both the clockwise and anti-clockwise circulation, which mainly cancelled out each other in the interface region between the vortical structure and the cocurrently flowing water. Whereas, in the region near the nozzle exit, the vortical structures were of opposite signs in regions above or below of the nozzle exit. As mentioned before, the fluctuating velocities were measured both above as well as below the nozzle, using an array of the seven HFA sensors traversed along the axial direction opposite to the direction of steam-water mixture flow. The vortical structure formed due to the spontaneous injection of the steam for varying time durations resulted into wavy flow profile along the axial axis of the cocurrently flowing water, which might mainly be attributed to the breaking of the circulating vortical structure. However, the wavy profiles did not appear at all the injection times at the same spatial positions rather the length across, which such structures were observed, varied proportionally with the injection time. This wave motion appeared each time thus all the way till the last measurement point location negating the creation of any other instability inside the fluid domain. The velocity fluctuations of the flowing steam-water mixture varied with the time duration at which the steam was injected into the water. The circulating vortical structure and the water surrounding it comprised of the three regions, which are the ambient, the central core region and the interface between the steam induced vortical ring and the ambient water. The core diameter varied with the time duration at which the steam has been injected inside the flowing water. It was larger than the corresponding length across which it prevailed and then decreased with the passage of time. It is interesting to state here that the growth rate of this circulation depends mainly on the entrainment of the surrounding water. However, the circulation motion diminished at a distance away from the exit of the nozzle, it is, therefore, the growth rate of the large vortical structure underwent through major changes as the core region of the circulation also varied. A possible reason of restricting the circulation between the steam and the co-currently flowing water could be the buoyancy influence of the steam, which destabilized the interface along with the momentum-driven entrainment that impacted the flow in a negative way, an observation that was convincingly supported by an earlier study (Maxworthy, 1974).

3.2 Circulation flow ring and Vortical Structures inside the flow regimes

The steam injected in this phase of the experiment for time duration varying from 10-60 seconds. The data were acquired at 0 - 20 cm from the nozzle exit. It should be noted that there are few points where the velocity fluctuations have shown a repetitive behaviour. The variations and fluctuations of the

velocity have shown the most repetitive (6%) and dominant character at different points within this range. The vorticity distribution had shown a decreasing trend as soon as the array of sensors were traversed away from the starting position, i.e. 0 cm. This decrease indicated a monotonic character, in general, all the way till the distance, 16-20 cm away from the exit of the nozzle, however, from this onward, the velocity fluctuations represented a wavy character. The decreasing trend shown by the time-averaged velocity fluctuations clues towards the diffusive character of the steam induced vortical ring at its periphery where it entrained the surrounding fluid giving birth to the comparatively higher fluctuations at the outer region within the cocurrently flowing water. This can be seen in the plot of the fluctuating velocities in Fig 2(a) at the above-said distance. One important observation recorded within the region comprised of the length segment, 12-18cm, is the weaker vorticity than the vorticity observed at the distance of 2.5 cm from the nozzle exit. Accompanying to this, the circulation (equation 2) obtained for the core region has been compared to the local circulation (equation 3) recorded along the downstream area using the angular velocity distribution. It has been observed that the values of the circulation even along the downstream area are still considerable than the values of the total circulation at the central core, as shown by Fig 2(b). In addition to it, the dependence of the dimensionless diameter associated with the central circulation vortical structure was also obtained. The dimensions of the circulating ring were also estimated with the help of the equation 4, where the values reversal gives us the indication of the opposite sign vorticity at the interface as shown in Fig 2(b). The results have shown that for all the injection time durations (10-60sec), the dependence of the circulating vortical structure was very weak at the varying injection time. It was also confirmed that even the Reynolds number also didn't add any dominant effect on the diameter of the ring, this finding is in line with an earlier study (Lies and Didden, 1976a).

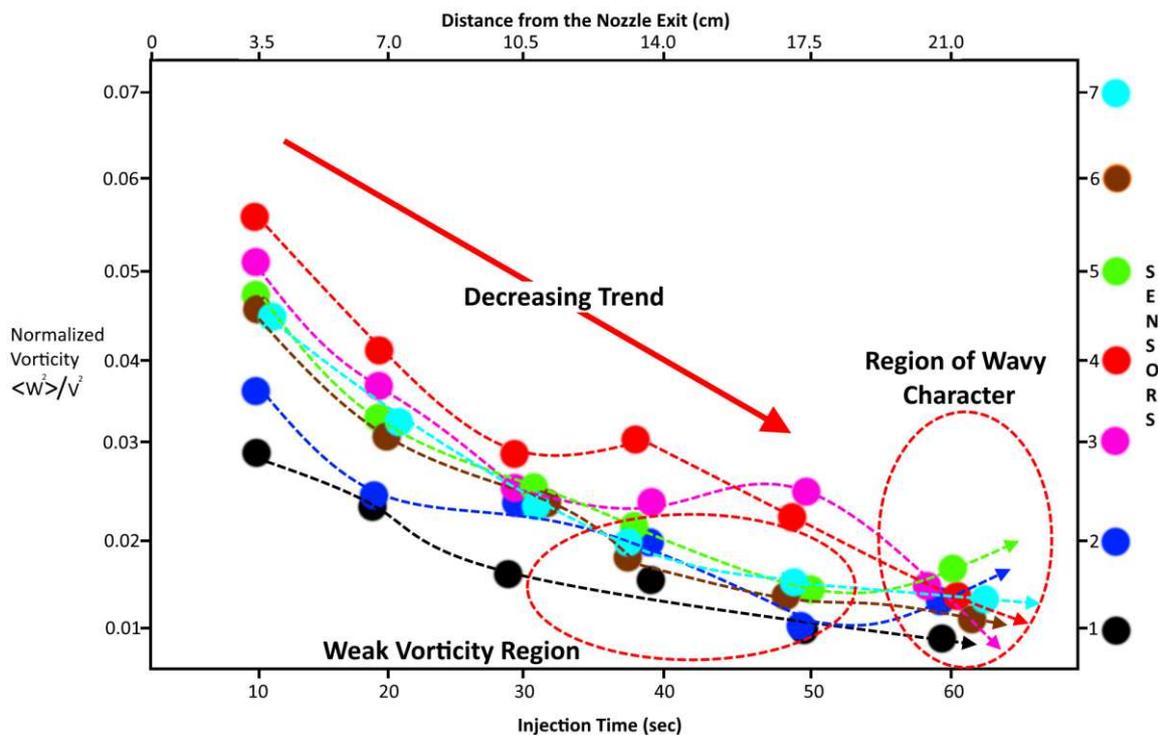


Figure 2(a). Normalized vorticity along the flow channel

The dependence of the length of the vortical circulation ring land diameter against the steam inlet pressure (5 bars), and injection time was also determined. It was estimated by first assuming that the velocity (U), which was measured on the average basis at the exit of the steam nozzle had a uniform distribution and the length (L) of the Steam induced vortical (Γ_0), during the time duration, t is given by the relation as follows (Kulkarny, 1977),

$$\Gamma_0 = \frac{1}{2} \int_0^t U dL \quad (4)$$

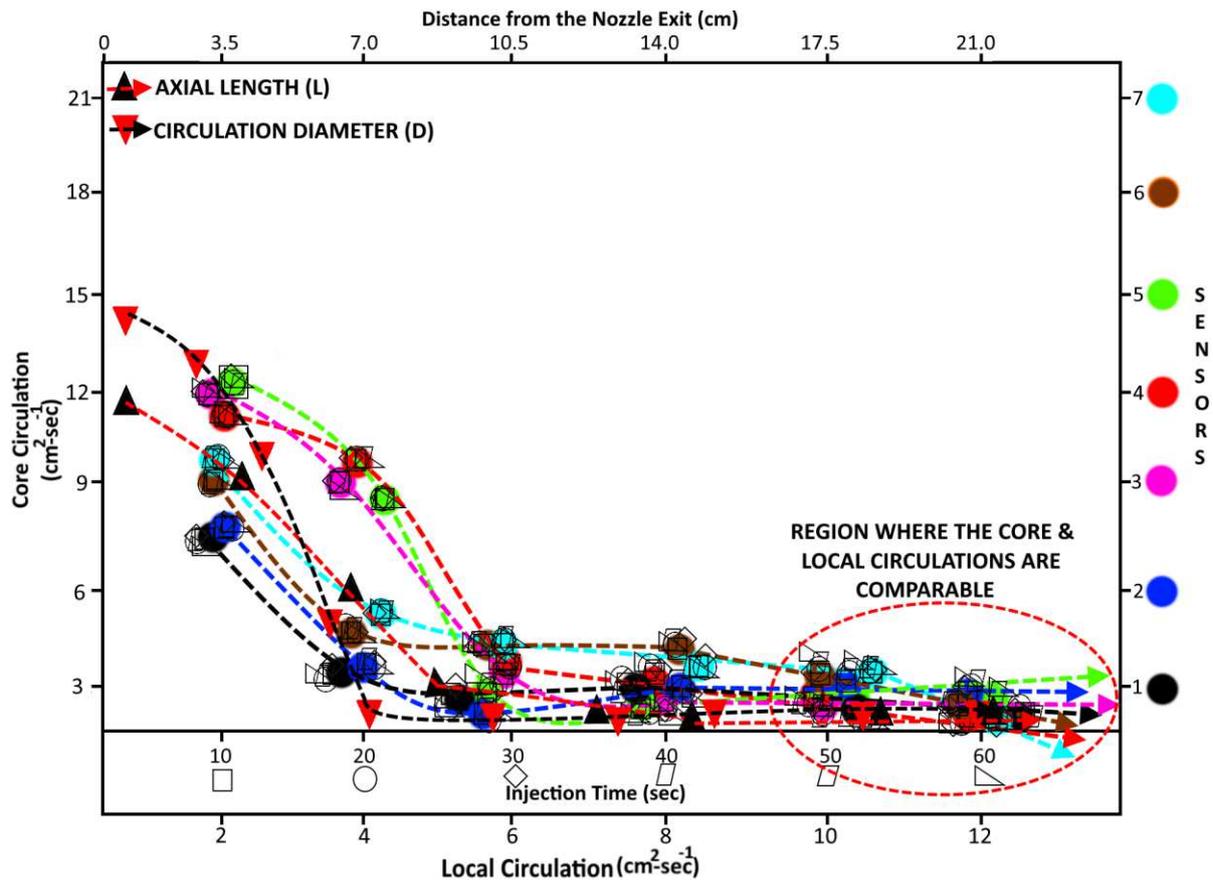


Figure 2(b). Core versus central circulation within the steam-water flow

This is the simplest equation supporting the impulsive flow, yet it did not account the effects imparted by the vorticity at the edges of the nozzle exit. It should also be noted that the length of the vortical circulation was measured with the help of the equation 3, whereas, its diameter was measured with the help of the equation 2 and the negative values of the vorticity provided the information related to the approximate spatial positions where the interface between the surrounding fluid and the circular vortical ring existed.

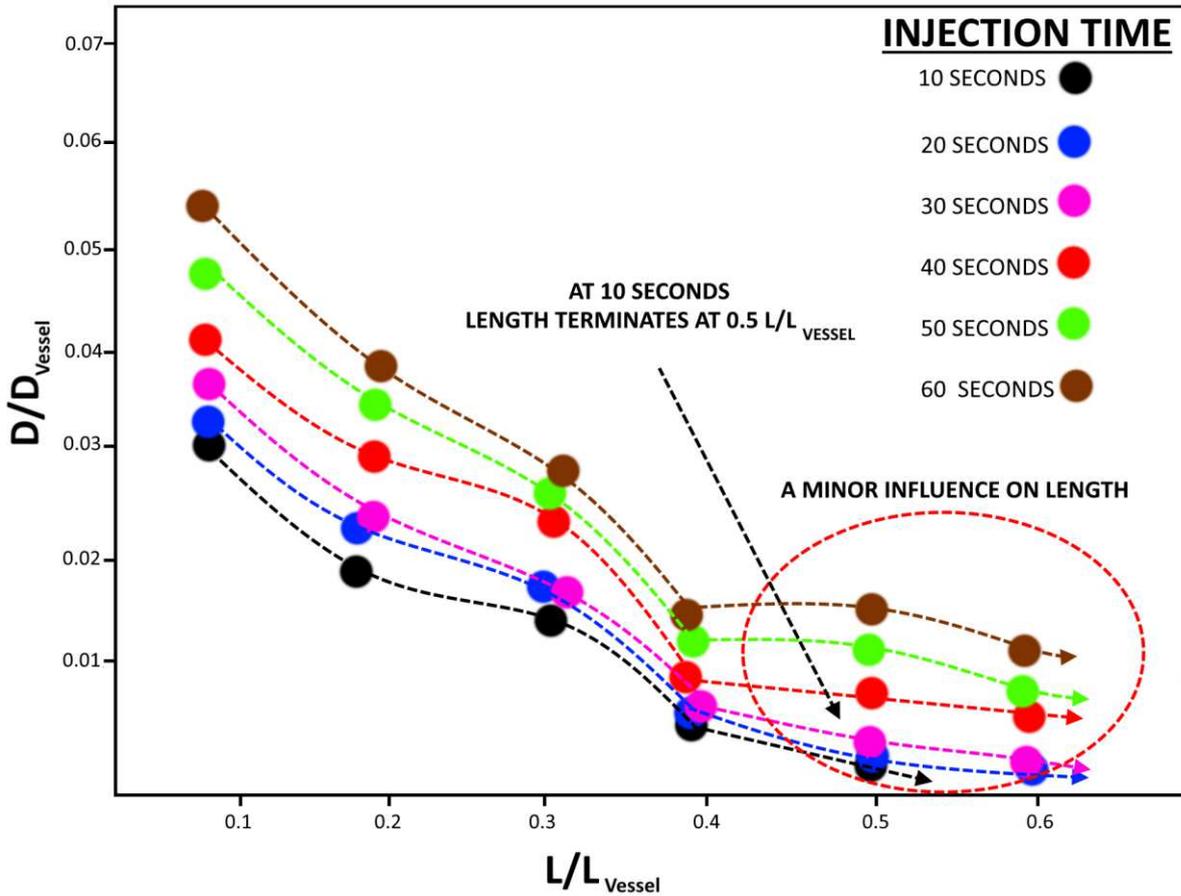


Figure 2(c). Dependence of length and diameter on the injection time

3.3 Effect of Injection time on the instabilities inside the flow regime

It should also be noted that when traversing the velocity sensors, flow instabilities were measured inside the flow which remained dominant till the time when the steam was injected into the water and the flow dissipated after the valve for steam injection was shut after steam's injection for a specified time period. The instabilities being observed here, were analogous for the similar instances in the earlier studies (Krutzschnig, 1939; Liess and Didden, 1976b; Maxworthy, 1972; Moore, 1974; Widnall, D O N A et al., 1974; Widnall, S. E. & Sullivan, 1973) with variations in steam injection duration or variations in Reynolds number. However, a few interesting trends of the instabilities' wave number can be seen in Fig 3.

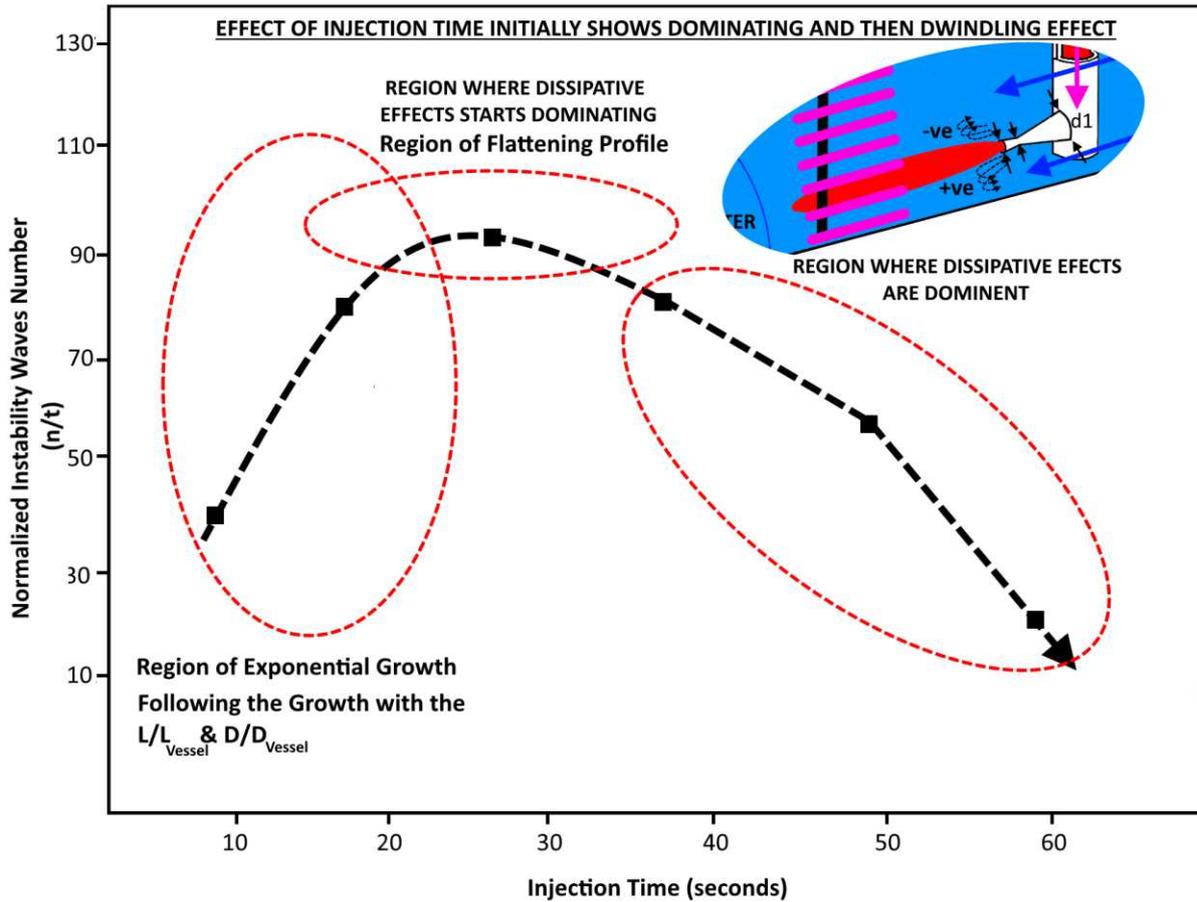


Figure 3. Effect of injection time on Normalized Instabilities Waves Numbers

The wave number follows almost an exponential trend till the injection time ~ 20 seconds, before it smoothed along the horizontal. This curvy trend has been observed in the time domain range, 20-30 seconds. Afterwards, it shows an increasing trend initially; however, then suddenly a decreasing trend can be seen which emphasizes the dominant role by the dissipative effects in the current flow regime. A straight forward reason for such a behaviour is due to the instabilities that have first shown an increasing trend, which is consistent with the dimensions of propagation of the circulation vortical ring which afterwards has been broken out, with the resultant profiles have shown gradually flattening profiles due to the dissipative character under the action of such dissipative forces. Although, the phenomena of the pulsating fluid injection into the water was described by a number of studies that included mostly the visualization studies, but here in the current manuscript we quantitatively discussed the effect of the pulsating steam injection into the water on the flow regimes involving interaction between steam and water. It should also be noted that we do accept the non-frozen nature of the date, but still on the average basis, the fluid regime has been characterized as much as we can. So far the accumulative results have been concerned which can be drawn on the basis of the results discussed till yet, It was found that the core region which was emerged, but remains attached to the nozzle exit and with the rise in the injection time, only a slight rise in the length of the core region was observed. But still, the main core that was responsible for giving birth to the forward rolling large vortical structures, which remained attached to the lip of the nozzle with just a minor depressive flow profile (observations

were guessed on the basis of the data from the HFA sensors) near the nozzle exit that was due to the sudden expansion of the steam jet as soon as it emerged from the nozzle exit. The steam's jet injection into the water in a pulsating mode resulted in the formation of the vortical structures, with small values along the periphery of the jet which had opposite signs in the upper and downward sides mainly due to the negative and positive gradients of the velocities along the horizontal and vertical directions as shown by the inside picture in Fig 3.

The quantitative balance between the positive and negative vorticities across the steam-water interface in the upward and downward directions of the steam's nozzle exit, cannot be measured due to the lack of present experimental capabilities to characterize the fluids from this point of view. However, on a generalized basis, it can be said that the balance may depend on the Reynolds number and on the duration of injection of the steam and the suitable location for such a measurement could be the region in the vicinity of the nozzle exit. Earlier studies (Moore, D. W. & Saffman, 1973) investigated the exact effect of the Reynolds Number on balance between the pulsating injection-induced positive and negative vorticities. However, further studies (Maxworthy, 1977) conducted after this revealed that the correlations didn't agree with the experimental measurements, even the earlier efforts (Moore, D. W. & Saffman, 1973) in which it was declared that the injected fluid rolls up in the forward direction, thus induced vorticity from various viscous processes at the nozzle exit resulted into an underestimations in predicting the experimental data.

Yet such efforts didn't exactly predict the exact balance between the positive and negative vorticities but still the basic physical phenomenon that can be used as a basis for modelling such case, cannot be simply denied as a whole, since still in the region far from the injection point the viscous dissipation surely can become dominant over inertial forces to break down the large circulating structures.

3.4 Flow Hydrodynamics in the region far from the steam nozzle

It has been observed in a number of studies (Afrasyab et al., 2013; Khan, 2014; Khan et al., 2016b, 2016a, 2013) that the instabilities at the interface have lower amplitudes in the region near the nozzle exit which has been transformed into larger and larger amplitude instabilities as soon as the steam propagates into the water. Amplitude of such instabilities after some finite rise break down into the ring-like vortices, which causes the interaction between the fluids at the interface. A possible reason for such a behaviour can be seen in earlier studies [19] where an imbalance between the axial wave number and radial mode number was claimed (Widnall, D O N A et al., 1974). According to the observations quoted in the given studies, the breaking of the outer core did not take place uniformly, rather occurred in azimuthal direction with the formation of a net flow. It was further observed in another earlier study (Leibovich and Randall, 1972) which claimed the propagation of just a single wave along the central core and the wave had a finite amplitude and a large axial velocity. Due to the large axial flow velocity, the central core wave in the far-off region had a profound effect on the regime owing to the ring instability.

The measurements at the far region from the nozzle exit, exhibited a non-frozen nature which depicted the highly fluctuating nature of the flow regime. The velocity fluctuations measured at the central core were having less amplitudes than the velocity amplitudes at the periphery of the circulating region.

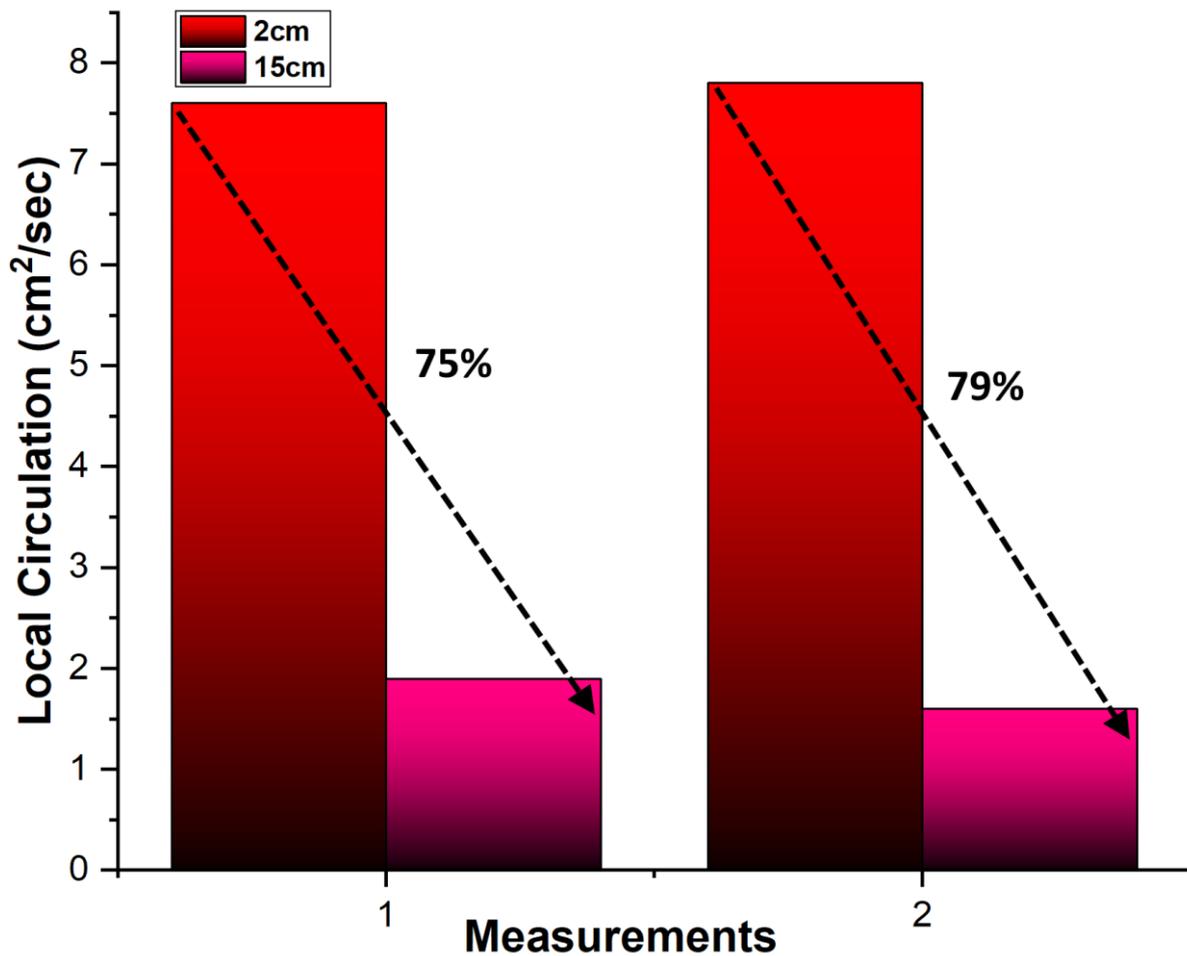


Figure 4. Comparison of Local Circulations at different locations along the axial axis

The main reason for this may be the higher axial mean velocities, and fluctuations in the velocity were marginal compared to the mean values. Also, the interface appeared to be turbulent at the far regions as well, and this was characterized due to the formation of the vortical structures owing to the entrainment of the surrounding water. The variations in the magnitudes of the vorticities in the far region were relatively large owing to the stronger interacting between the steam and the surrounding water. To fully understand the effects imparted by the vortices and the turbulence at the far regions from the nozzle exit, the local circulations at two distances, i.e. 2 cm and 15 cm from the nozzle exit, were obtained (see Fig 4), which were when compared with the core local circulations at the distance of 2 cm, the local circulation was found to lose 75-79% of its circulation at a distance of 15 cm as shown in Fig 4.

CONCLUSION

An experimental study was performed to highlight the hydrodynamics in a desuperheater's vessel, when the pressurized pulsating steam was injected co-currently with the slow-moving water in the cylindrical vessel. The velocity fluctuations associated with the steam-water mixture were obtained using an array of 7 HFA sensors, traversed axially across the flow domain. The measurements obtained against the steam injection duration varying from 10-60 seconds and along the axial distance of 0 – 20 cm from the nozzle exit, showed a decreasing trend for time-averaged velocity fluctuations, which hinted to the diffusive character of the steam's induced vortical ring at the periphery of the circulation associating to the entrained water giving rise to comparatively higher fluctuations at the outer region of the ring. Within the length of 12 – 18 cm from the nozzle exit, the vorticity was weaker than the vorticity obtained at the distance of 2.5 cm from the nozzle exit. Also, the formation of the vortical structures having small values along the periphery of the jet was found, which had opposite signs in the upper and downward sides mainly due to the negative and positive gradients of the velocities along the horizontal and vertical directions. Influences due to the vortices and the turbulence at the far regions from the nozzle exit was determined by determining the local circulations at 2 cm and 15 cm from the nozzle exit. The core local circulations at the distance of 2 cm from the nozzle exit, was found to lose 75-79% of its circulation at a distance of 15 cm from the nozzle exit.

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Figures

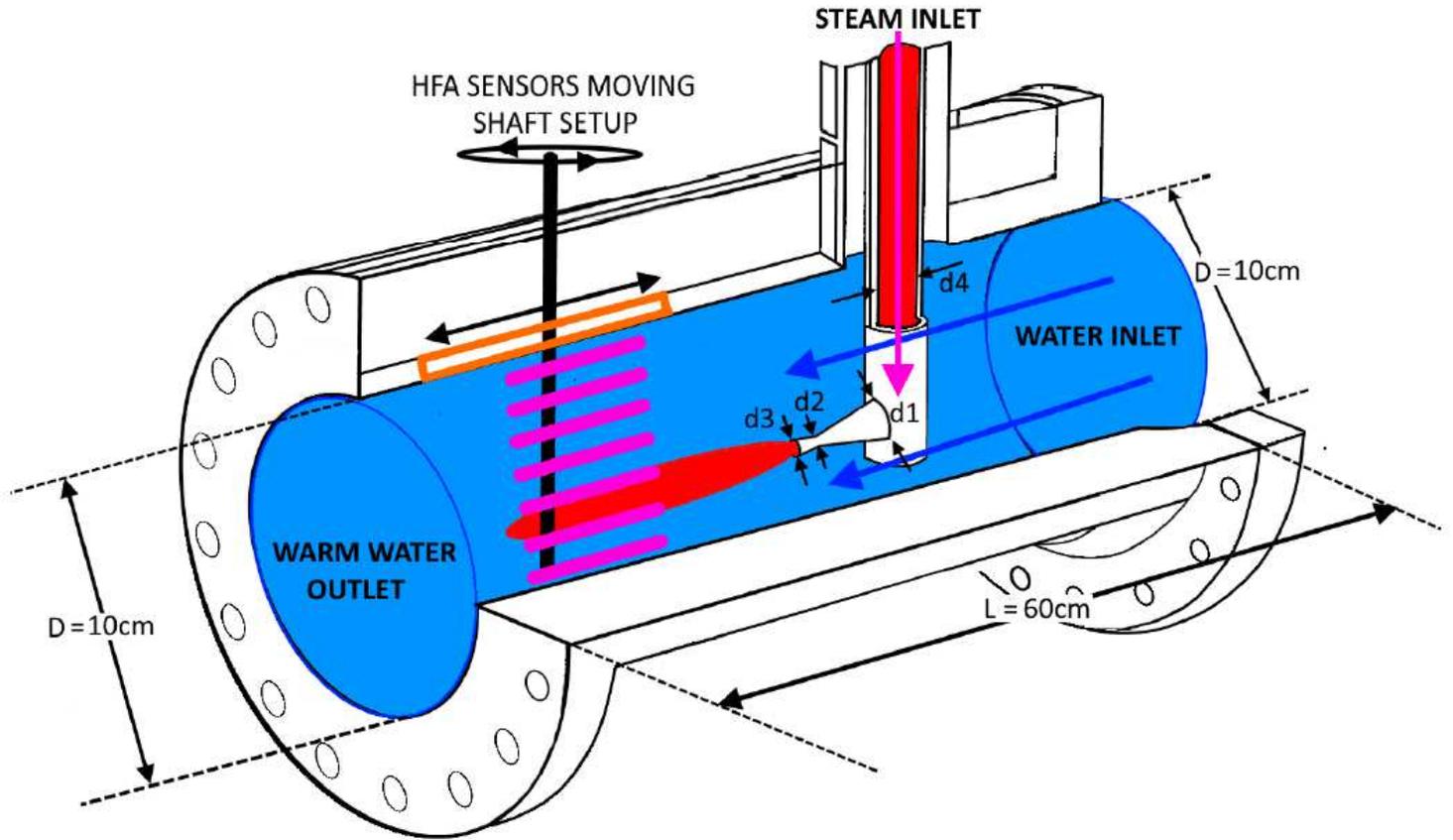


Figure 1

An experimental Setup (Desuperheating vessel)

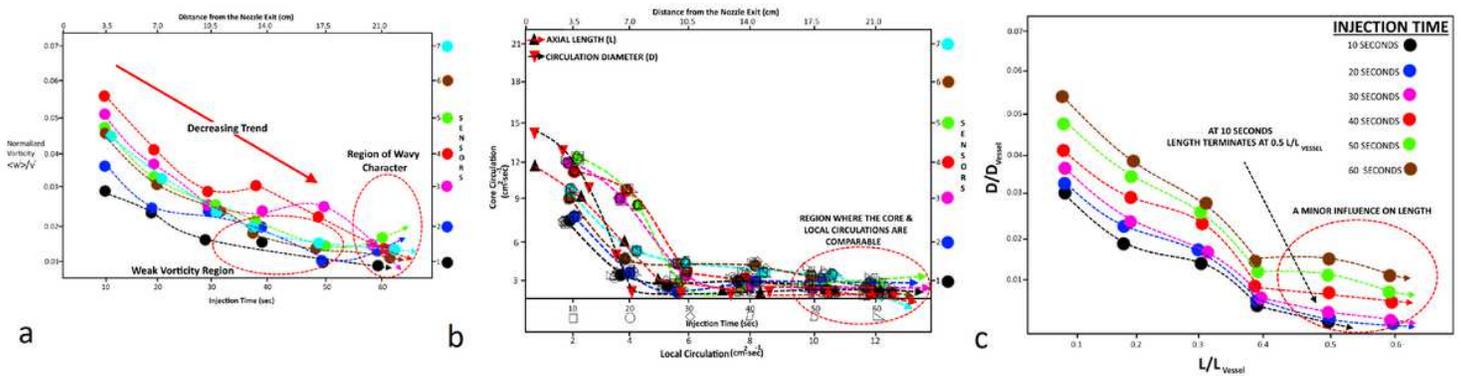


Figure 2

(a). Normalized vorticity along the flow channel. (b). Core versus central circulation within the steam-water flow. (c). Dependence of length and diameter on the injection time

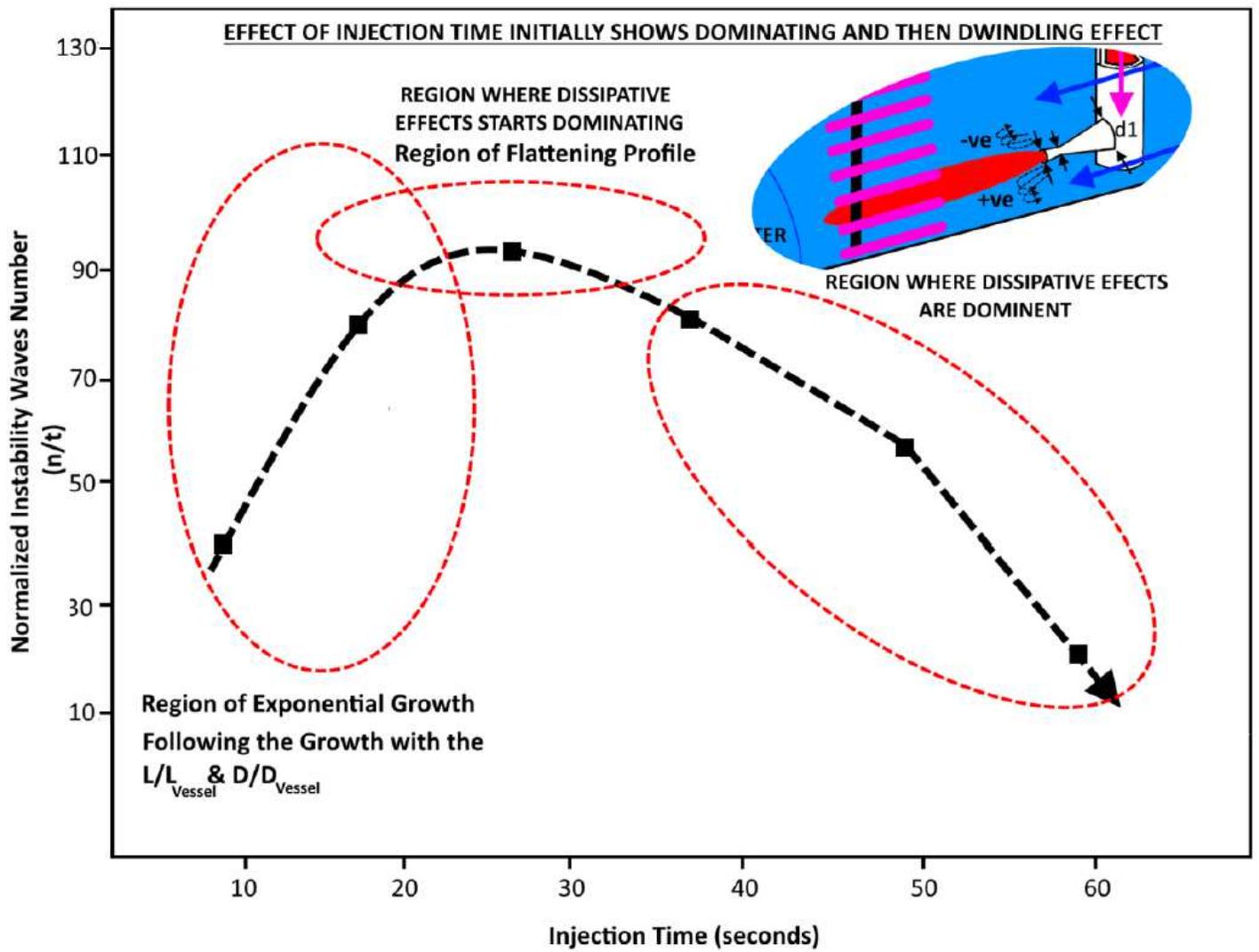


Figure 3

Effect of injection time on Normalized Instabilities Waves Numbers

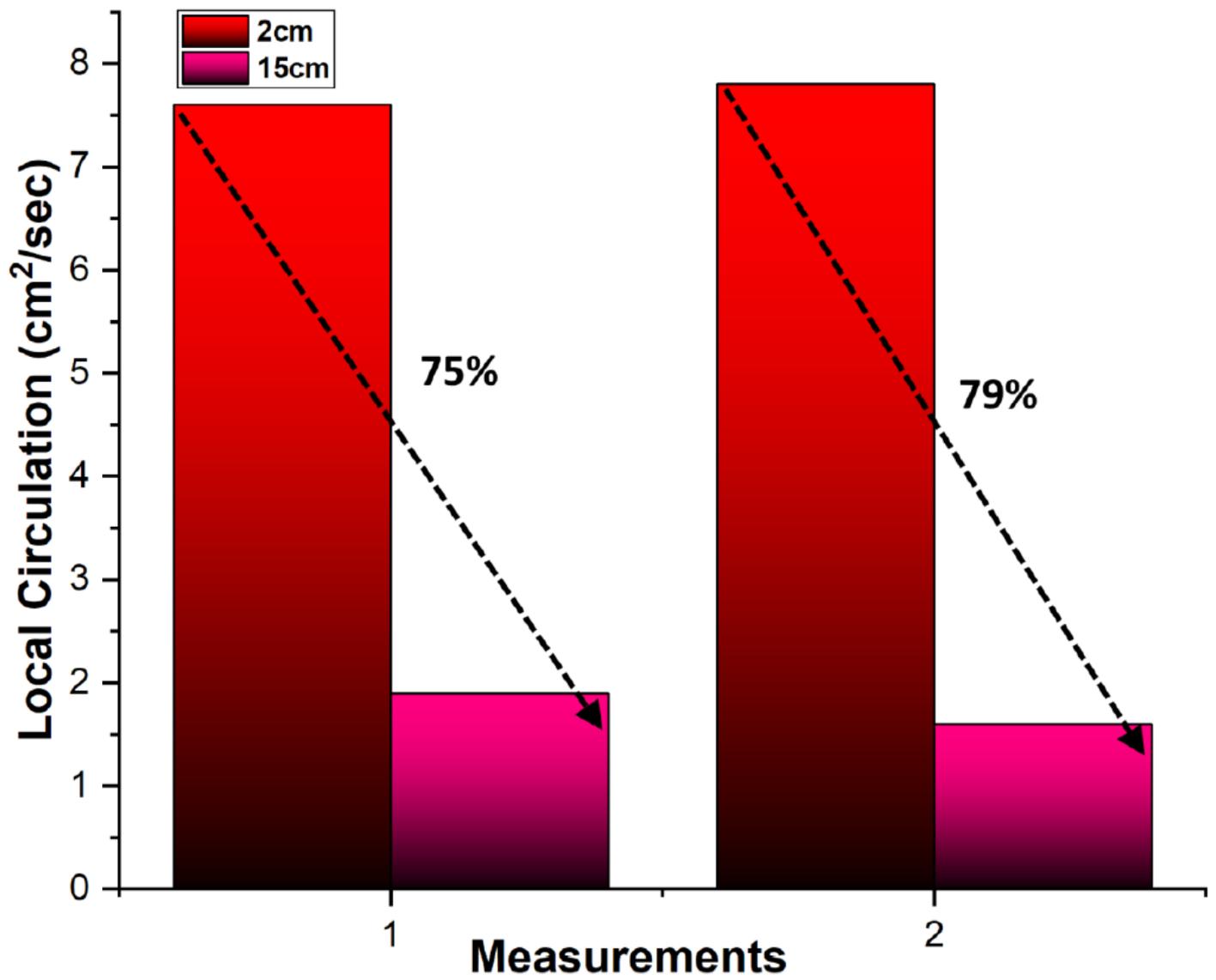


Figure 4

Comparison of Local Circulations at different locations along the axial axis