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FRETTING WEAR PARAMETRIC ANALYSIS OF FLEXIBLE TUBE IN HEAT EXCHANGER TUBE BUNDLE

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ABSTRACT

In the present study, an instrumented central tube's wear analysis was carried out in a tube bundle with a triangular configuration having parallel tubes. The pitch to diameter ratio (P/D) is 1.45. The fluid i.e. water's velocity in cross-flow increases from 0.18 to 0.55 m/s in equal increments of 0.09 m/s. Tests were carried out using five distinct flow velocities along with three unique time intervals (i.e. 60, 90 and 120 minutes). A Scanning Electron Microscope (SEM) is utilized during experimentation to examine the scars and gauge the wear scar dimensions developed on the surface of tubes. It can be seen during vibrations analysis that the amplitude of transverse vibrations increases considerably when we move past the velocity of 0.27 m/s and monotonically increases till the maximum velocity i.e. 0.55 m/s is reached. This analysis concludes that considerable wear is caused in the transverse direction at higher velocities. Examining the wear area points out that there is no unusual change in it against all the time durations up till 0.37 m/s, but once this value is surpassed the wear area inclines towards an appreciable increase with an increase in cross-flow velocity. The analysis of wear volume suggests that wear volume with increasing cross-flow velocity shows an increasing trend. There is not any considerable change in the pattern of wear volume against 60 and 90 minutes time intervals even at higher velocities. The change is observed against the 120 minutes interval; as the behaviour becomes quite distinct and displays a notable increase in the wear volume.

Keywords: cross-flow, flow induced vibrations (FIV), flexible tube, tube bundle, wear.

INTRODUCTION

The vibrations in the steam generators and heat exchangers is a crucial problem that reduces the amount of heat transfer during different processes in the industry. The cross-flow fluid forces developed in the shell side are a source of excitation for the loosely sustained tube bundle. The vibrations in the tube bundle is a major problem for operators and process engineers because these vibrations cause tube fretting wear, tube damages due to collision, enhanced clearance in baffle holes, tube leakage and fatigue failure. Generally, upon increasing the overall dimensions of the heat exchanger the shell side fluid velocity increases as well. Subsequently, it causes an increase in heat transfer rate. The clearance between the baffles and tubes allows the tubes to expand during heat transfer, but this clearance also gives way to flow-induced vibrations in the tube bundle. The amplitude of these vibrations is quite high near and around the critical fluid velocity. These vibrations consequently result in fretting wear and necking of the tube bundle. So, flow-induced vibration (FIV) in heat exchanger lead to equipment collapse and hence are responsible for extensive damage repair and process shutdown. Tubes in a tube bundle are loosely supported at each baffle and at times the support spacing is unequal. In nuclear power plants, the reactor parts like heat exchanger tube bundles, fuel rod assembly and piping section are modelled as multiple supported beams. It is imperative to find out if any of the tubes have a natural frequency within the operating range, which in turn might resonate with the tube bundle structure. Considerable research work is carried out which highlights the gravity of the fretting wear problem caused by FIV in tube bundles. Fretting wear mainly involves many wear mechanisms like abrasion, adhesion, delamination, fatigue & corrosion. Blevins & other research groups have been investigating the wear process in heat exchanger tubes since 1970. Those researches have added vital knowledge to the database that helps in comprehending the wear mechanisms (Ko 1987). The research shows that the wear in tubes is usually more distinct, critical and damaging when a gap is present (Kim and Lee 2003). Rather than just considering a sliding mechanism; a sliding, as well as an impact mechanism, was used for the investigation to depict higher wear rates in presence of a gap. Many wear mechanisms are present in the heat exchangers domain and it is observed that usually, multiple mechanisms play their role in a specific wear case. Adhesion and abrasion (Iwabuchi 1991, Hartman, Britton *et al*. 1992) are termed as chief fretting wear mechanisms. Adhesion is responsible for commencing fretting wear and abrasion kicks in after the oxidization of the particles (Ko 1987). The particle dispersal substantially affects the rate of fretting wear. As we know, it's an important task for design engineers to assess the life of equipment and structure. Meng and Ludema (Meng and Ludema 1995) outlined the currently present wear models. The literature reveals that wear depth, wear volume and loss of weight are the three crucial parameters for studying wear as they govern the wear severity. The 'work rate model' was developed based on these parameters and this model has been used to determine the wear of nuclear steam generator tubes (Fisher, Chow *et al.* 1995) and nuclear fuel tubes (Joulin, Gue´ rout *et al.* 2002).

The perforation and structural integrity of tubes are a function its thickness, however, the depth of wear in tubes rather than the wear volume is more critical. The maximum depth of wear is quite arbitrarily localized because the vibrations and collisions of each tube in the bundle are a bit different from the others. This makes it hard to ascertain the maximum depth. This is due to a sophisticated volumetric shape of tube wear (Kim, Lee *et al.* 2006). If we consider a different local wear mechanism then this phenomenon of arbitrary maximum depth can be illustrated well. The current need is to develop a parameter that can accurately define the severity and level of wear; to efficiently deal with the cases in which the main interest lies in thickness reduction. In some interesting early studies, Connors (Connors 1981), Blevins (Blevins 1978) and Ko (Ko 1985) predicted fretting wear. Connors introduced the algebraic formula for rocking motion wear scars that were in the form of a crescent and a pyramid. Au - Yang (Au-Yang 1997) has investigated the flow-induced wear in tubes for steam generators, comparing its findings with current operations. He considered the gap effects and concluded that the main reason for wear is not only turbulence agitation but also turbulence excitation and fluid-elastic force, under 15 effective full-speed years (EFPYs). Yetisir *et al.* (Yetisir, McKerrow *et al*. 1998) have proposed a linear rate of work to predict damage to the heat exchanger tubes caused by turbulence wear. Pettigrew *et al*. (Pettigrew, Carlucci *et al*. 1991, Pettigrew, Taylor *et al.* 2003) studied the fretting wear loss of vibrating components and steam generator techniques to model the dynamic interaction. They also studied the tube wear caused by the non-linear interactions between the tube and the baffle caused by clearances between two interacting parts (Khushnood, Khan *et al*. 2004). An experimental investigation was performed to understand the behaviour of the wear mechanism against the vibration response for different flow velocities (Abbas, Khushnood *et al.* 2017, Usman, Khushnood *et al*. 2019). The current work emphasis on the parametric analysis of the fretting wear effects due to flow-induced vibrations on tube bundle.

EXPERIMENTAL SETUP

Experimentation setup comprising of Close loop Water Tunnel at low speed is available at MED, UET Taxila. This water tunnel was originally designed for velocities between 0.18 m/s and 0.55 m/s. The converging and diverging part of the tunnel is made of metal and the test section consists of acrylic plates as shown in Figure-1. The dimensions of the test rig are 200 mm x 100 mm and consists of jointly screwed acrylic plates. A 200 gallons water reservoir along with a 10 HP centrifugal pump is installed to sustain the water flow in a closed loop. Valve 1 and Valve 2 i.e. main valve and bypass valve respectively are provided to regulate the water velocity inside the test rig as shown in Figure-2. In the test section, a Doppler type ultrasonic flow meter was used to measure the water's upstream velocity. The transducer for flow measurement was installed externally on the test rig because of its working nature. Water is first pulled from the reservoir; then accelerated by the pump and lastly passed through the test rig. The purposefully arranged flow straightener ensures that there is a uniform velocity distribution having less than 3% turbulence intensity. The tube bundle undergoing examination is installed in the test rig and the required flow around the tubes is generated within the tube bundle while the medium flow is in motion. The tube bundle drawing and the image is shown respectively in Figure-3 and Figure-4. Aluminium tubes were used to form a triangular bundle of parallel tubes. In Figure-3, the black mark indicates the tube position, whereas Y displays a stream-wise direction while X shows the transverse direction.

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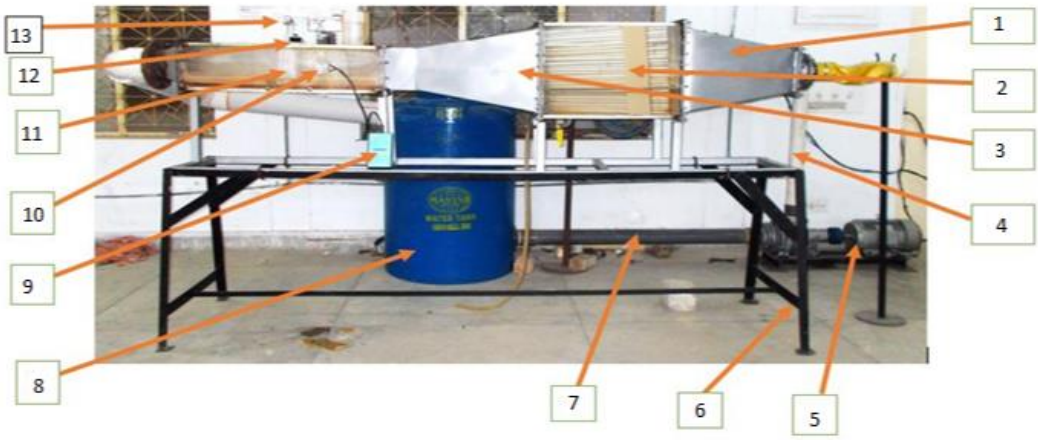

Figure-1. Closed-loop low-speed water tunnel.

1. Divergent Section	2. Flow Straightener Section	3. Convergent Section	4. Pump Delivery Line
5. Centrifugal Pump with 10 HP Motor	6. Water Tunnel Stand	7. Suction Line of Pump	8. Water Reservoir
9. Doppler Flow Meter	10. Flow Meter Transducer	11. Test Section	12. Accelerometer
13. Tube Bundle			

Figure-2. Mechanism for flow control (1) Test Rig (2) Valve 1 (3) Valve 2 (4) Water Reservoir.

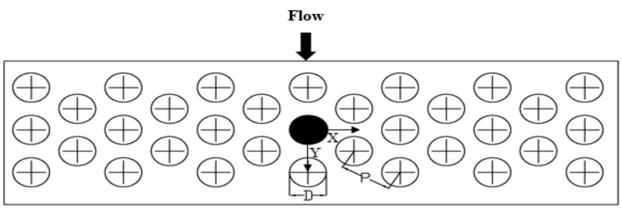

Figure-3. Tube bundle schematic diagram with P/D of 1.45(X=Transverse, Y=Stream-wise).

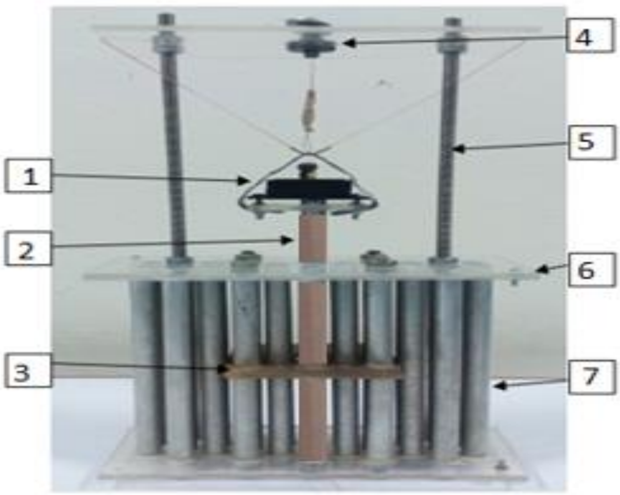

Figure-4. Tube Bundle (1) Accelerometer (2) Monitored tube (3) Baffle (4) Tensioning mechanism (5) support stud (6) support plates (7) Rigid tubes.

The accelerometer (wireless) was installed on the top of the monitored tube to observe the vibrations in the direction of flow (Y) and transverse direction (X). The monitored tube's natural frequency was set to 8±0.1 Hz. A tensioning mechanism is provided using 0.2 mm thick piano wires to alter the monitored tube's natural frequency. An accelerometer was set up on the monitored tube's top to measure its vibration response in the cross-flow. The entire assembly was sustained by the two acrylic plates, one for holding the fixed tubes and the second for holding the tension generating mechanism Figure-4. Table shows the tube bundle's specifications. The tube bundle holding plates were designed and developed to fit into the space allocated in the water tunnel test section. The plates were typically 200 mm x 90 mm in size so that they can be easily placed in the test section.

Table-1. Specification of the tube bundle.

Tube material	Copper
Tube arrangement	Parallel triangular
Mass of the tube	0.186 kg
P/D ratio	1.45
Tube outer/inner diameter	13.5 mm/ 12.5 mm
Tube length	230 mm
Modulus of Elasticity	117000 MPa
Density of water	1000 kg/m^3
Baffle thickness	0.6 mm
Baffle hole diameter	16 mm
Tube to baffle radial clearance	1.25 mm

The plates were firmly secured in the test rig before performing the tests to avoid any errors during the experiment. The tests were carried out at five distinct flow velocities with each increment of 0.09 m/s. Three different time intervals i.e. 60, 90 and 120 minutes was selected for the experimentation to develop the trend of wear that can analyze the life of material against each flow velocity. A total of 15 experiments were carried out. The data acquisition loop for measuring the monitoring tube's vibration response consists of the wireless tri-axial accelerometer sensing node G - link together with the WSDA Wireless USB Base Station connected to the PC through MICROSTRAIN Corporation's Node Commander Software. A sampling rate of 679 Hz was adjusted for the data acquisition system. Each accelerometer signal was averaged using the SIGVIEW software. The data obtained was saved in an excel file for further analysis. The time-domain signals of the vibration response were then converted to the frequency domain to obtain the frequency component of each signal by applying a fast Fourier transform (FFT), by using a software SIGVIEW developed by Signal Lab company. The acceleration signals captured from the wireless accelerometer were then calibrated and the RMS vibration amplitudes were obtained.

Experimental Procedure

The experimental procedure consisted of the fabrication of a tube bundle made of aluminium tubes and acrylic plates and testing them under different velocities in the water tunnel. The first step was to measure the flexible tube’s (copper) natural frequency. To measure the natural frequency, the tube was plucked gently i.e. a small excitation was given to the tube and then allowed to vibrate freely. A free oscillating acceleration signal was generated by the vibrating tube. The surrounding tubes were held rigid to evade their influence on the monitored tube, during the determination of its natural frequency. After determining the natural frequency, the flexible tube in the tube bundle was mounted in the water tunnel test section. Two acrylic plates held together through 500 mm long studs kept the tubes rigid (except the flexible tube).

Wear Parameters

A Scanning Electron Microscope (SEM) is used during experimentation to examine and gauge the wear scar sizes developed on the surface of the tubes. Total 15 specimens were developed after taking the monitored tube out of the bundle; they were to be tested for three distinct time-spans and five different velocities to gauge the dimensions of wear scars through SEM. The depth was measured by utilizing a new methodology. SEM was used to detect cross surface profiles of diverse specimens of already known wear depths on alike tube materials. These measurements helped us in the development of a calibration curve. This calibration curve gave us a conversion factor (1 ADU=0.3055 µm). Based on that conversion factor, wear depths of scars were assessed.

RESULTS AND DISCUSSIONS

Tube’s Vibration Analysis

Figure-5 depicts the tube’s vibration spectrum in the transverse and stream-wise directions against the velocity values of 0.18 m/s (minimum) and 0.55 m/s (maximum) and Figure-6 shows the RMS values of acceleration in the tube against the increasing trend of cross-flow velocity. It is quite clear that the tube’s vibration amplitude is very small at 0.18 m/s, apart from this the transverse amplitude is slightly higher than the stream-wise amplitude Figure-5 (a, b). The variation in the amplitude in each direction is considerable at 0.55 m/s; here the amplitude in the transverse direction is about 3 times that of the stream-wise direction as shown in Figure-5 (c, d). Tube vibration response is presented in an elaborative manner in Figure-6.

The stream-wise vibration amplitude indicates a minor rise within the considered velocity range, however, in the transverse direction; vibration amplitude increases drastically after the value of 0.27 m/s and continue to follow this trend with the increase in velocity. The maximum RMS value of acceleration amplitude is about 2 m/s^2 when the velocity is maximum. When the velocity reaches its maximum i.e. 0.55 m/s the tube starts to vibrate elliptically, therefore, the sliding contact of the tube with baffle increases and the RMS amplitude also increased suddenly.

The value of amplitude in transverse vibrations represents the response of the tube, and that is because of the tube’s impact on the baffle holes. This leads to considerable wear, mainly in the transverse direction, at high speeds. Thus, the acceleration amplitude appears to be in a robust relationship with the tube wear which has been discussed in the later sections.

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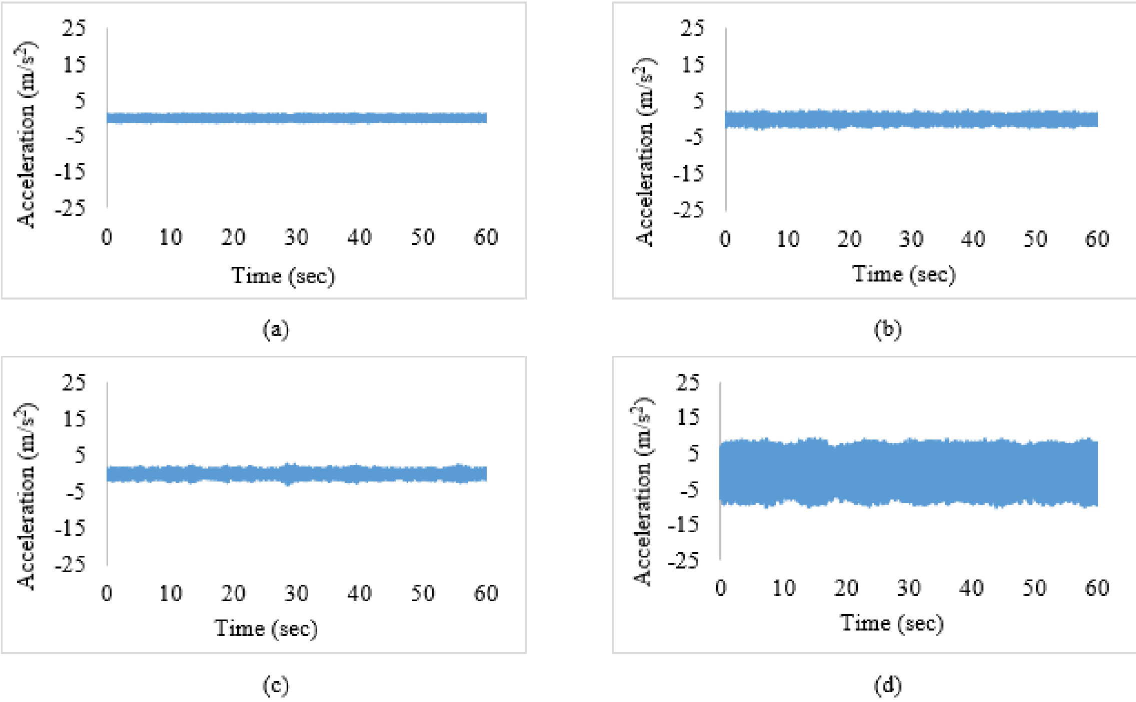

Figure-5. Tube's vibration response in stream-wise (Y) direction (a) Velocity = 0.18 m/s (c) Velocity = 0.55 m/s and in Transverse (X) Direction (b) Velocity = 0.18 m/s (d) Velocity = 0.55 m/s.

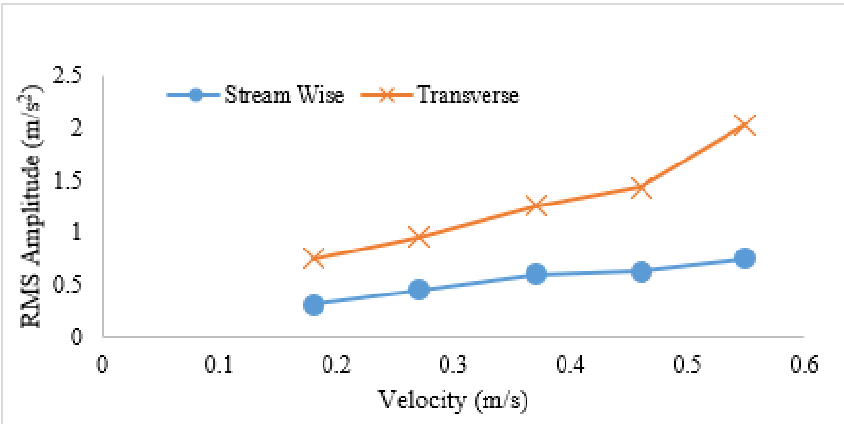

Figure-6. Tube's RMS acceleration amplitude response.

Wear Profiles

Figure-7 shows the tube wear profiles against the maximum velocity i.e. 0.55 m/s for different durations. The examination of wear profiles & attributes associated with it indicates that the wear width is inclined towards an incremental trend with increased tube and baffle interaction. The wear depth also shows the alike behaviour. Figure-7 indicates the small peaks in wear profiles against 60 and 90 minutes duration. This is a relatively small depth of wear and this was analyzed through SEM. For 120 minutes duration, a severe profile with reasonably larger peaks in magnitude are observed which shows that the wear depths are higher for this duration.

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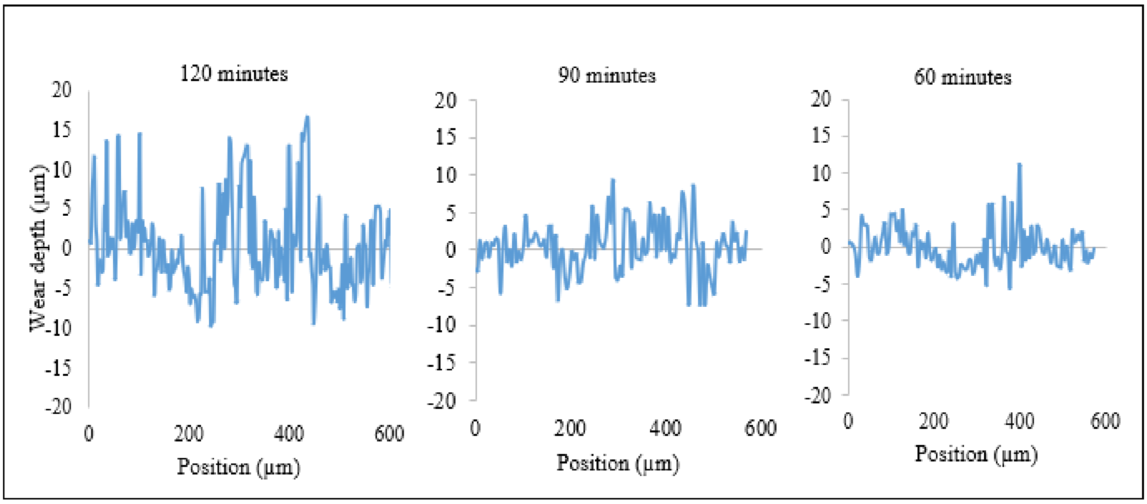

Figure-7. Tube's wear profiles at 0.55 m/s velocity (60 minutes, 90 minutes, and 120 minutes).

EXAMINATION OF THE WEAR DIMENSIONS

Wear Length

The variations in wear length are shown in Figure-8. It is visible that as the velocity increases, the wear length increases gradually. For the 60 minutes time duration, the length of wear was about 200 µm at speeds of 0.18 m/s and 0.27 m/s. Also, there is no considerable rise in wear length up to 0.27 m/s cross-flow velocity. However, the wear length shows a significant increase when velocity was higher than 0.27 m/s with the largest wear length of almost 1100 µm.

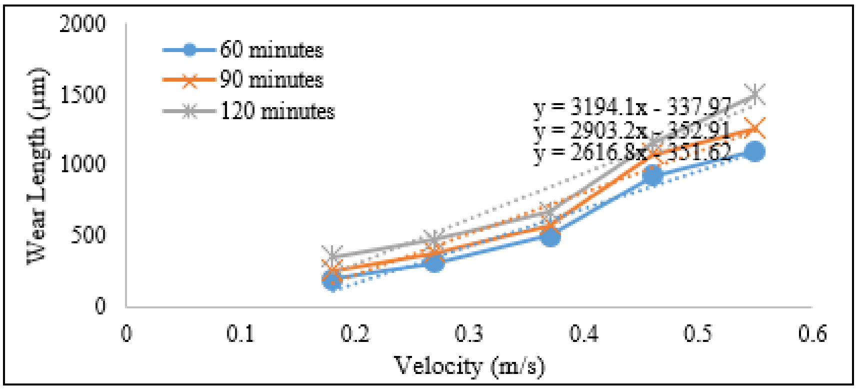

Figure-8. Variations in wear length vs cross-flow velocities.

This trend can also be seen for the other two interaction durations between the tube and the baffle, i.e. 90 and 120 minutes, except that the maximum wear length for 90 minutes was approximately 1260 µm and 1500 µm for 120 minutes interaction duration. It's also a noteworthy thing that as the interaction duration increases, the slope of the trend line appears to increase. The slops of trend lines are 2616 (µm/ms^{-1}), 2903 (µm/ms^{-1}) and 3194 (µm/ms^{-1}) for interaction duration of 60, 90 and 120 minutes respectively.

Wear Area

Figure-9 depicts the variation in wear area against all the durations with the increasing velocity. As it is quite clearly visible that there isn't any significant change in wear area against all the time durations till 0.37 m/s cross-flow velocity. The vibration amplitude also justifies this thing and hence lesser tube and baffle contact.

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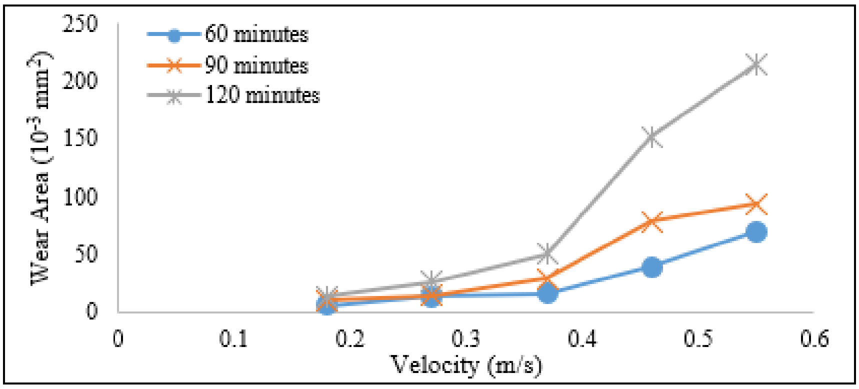

Figure-9. Tube's wear area vs velocities.

When the velocity surpasses 0.37 m/s value the wear area starts to rise considerably. Another vital point to note here is that the wear area pattern is unique for every single duration beyond the velocity of 0.37 m/s. After 0.37 m/s wear area increased sharply due to high amplitude which was generated because of the arbitrary elliptical vibrations of the instrumented tube. When the tube response depicted such vibrations, it was because the tube's sliding contact with the baffle had increased which resulted in enhanced wear width and consequently wear area suddenly increased as well. The maximum wear area of approximately 215 $\times 10^{-3}$ mm^2 was observed against maximum interaction duration i.e. 120 minutes and the minimum area was approximately 70×10^{-3} mm^2 for 60 minutes duration.

Wear Volume

Based on wear scar analysis and the depth estimation from wear profiles, a wear volume investigation was conducted to determine its correlation with different interaction durations & velocities. The pattern of tube wear volume against a set of considered durations and velocities is presented in Figure-10.

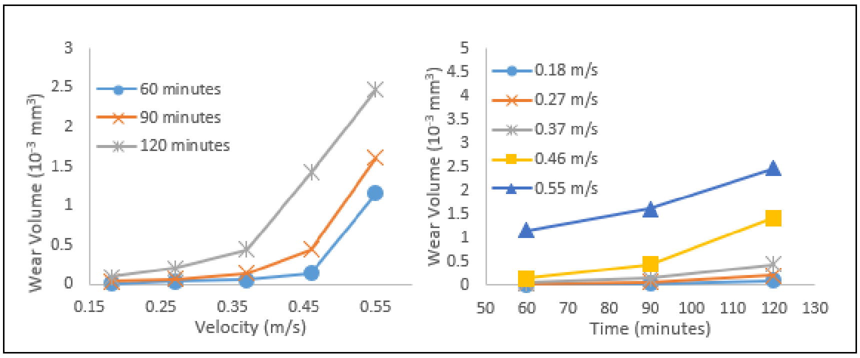

Figure-10. Tube's wear volume vs (velocities and interaction durations).

The analysis shows that as the velocity increases the wear volume rises as well. There is no considerable change in wear volume pattern against the 60 and 90 minutes duration even at higher velocity values. The maximum value was approximately 1.6×10^{-3} mm^3, but for 120 minutes the pattern becomes quite distinct and a considerable increase is observed in the wear volume which is approximately 87% greater than the other time durations as shown in Figure-10. The investigation further shows that the wear volume is relatively higher at a maximum speed of 0.55 m/s even at a duration of 60 minutes, which is otherwise very small for lower speeds. This analysis shows that there won't be any linear trend between the wear volume and interaction duration. A comprehensive study is needed that focuses on long-term wear analysis to have a deep insight regarding the wear volume behaviour.

Results Validation

The relationship between the wear area & wear volume of nuclear fuel rod and various contact forces was presented by H.-K. *et al* (Kim, Lee *et al*. 2006). The data from that article was taken for the experimentation of this work for comparison purposes, it's presented in Figure-11.

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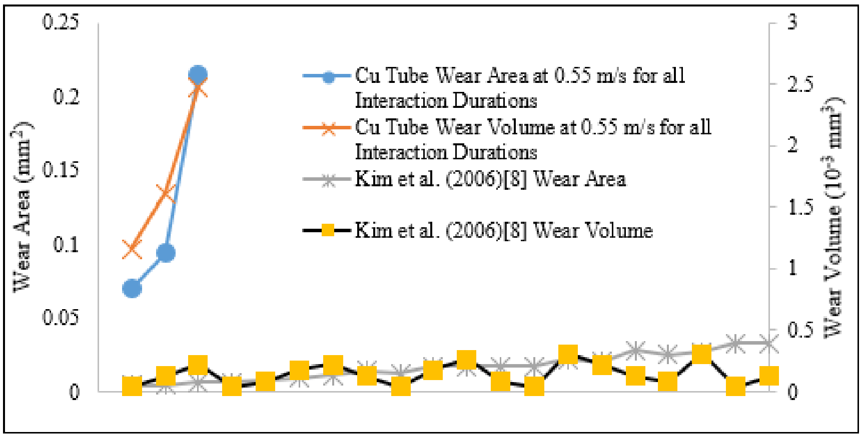

Figure-11. Comparison between wear volumes and wear areas of Cu tube & Zircaloy-4 Rod.

The trend against the low wear area for copper tube and nuclear fuel rod appears to be quite identical, but with the increase in wear area, the copper tube's wear volume is more accelerated than the nuclear fuel rod. The properties of specimen material may be the reason behind this synchronous behaviour. The material properties are given in Table.

Table-2. Comparison of mechanical properties.

	Current Experiment	**H.-K. Kim *et al.* (2006) (Kim, Lee *et al.* 2006)**
Material	**Copper**	**Zircaloy-4**
Mechanical properties		
Tensile strength	210 MPa	470 MPa
Yield strength	33.3 MPa	315 MPa
Elastic Modulus	110 GPa	136.6 GPa
Poisson's Ratio	0.343	0.294

Copper is comparatively a softer material, thus it shows a higher wear acceleration, whereas nuclear fuel rod (Zircaloy-4) is usually quite hard and that's the reason why we didn't witness any accelerated growth in the wear depth. The comparison presented in this work also verifies it.

CONCLUSIONS

In this work, the parametric analysis of fretting wear in flexible tubes of the heat exchanger was performed by using water tunnel, SEM and Node Commander Software. The tube bundle has a P/D ratio of 1.45, cross-flow velocity ranging from 0.18 m/sec to 0.55 m/sec with time intervals of 60, 90 and 120 minutes.

The results of this research conclude the following;

- The amplitude of vibrations in the transverse direction increases considerably when the cross-flow velocity surpasses 0.27 m/s value and the trend continues till the maximum velocity is reached. This analysis reveals that the wear generated at higher velocity values is primarily in the transverse direction.
- From the investigation of wear dimensions, it is evident that wear length escalates progressively with an increase in velocity. This investigation also suggests that the trend line slopes increase as the interaction duration between the baffle hole and tube increases.
- The wear area examination advocates that there isn't any significant change in it against all the three interaction durations till the cross-flow velocity of 0.37 m/s, but after that, the wear area is inclined to a significant rise.
- The wear volume analysis reveals a growing trend i.e. as the velocity in cross-flow increases the wear volume also increases with it. There wasn't any considerable change in wear volume pattern against 60 and 90 minutes interaction durations even at higher velocities but for 120 minutes the behaviour inclined towards a rise and became quite distinct.

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