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Experimental Analysis of Flow Induced Vibrations in Heat Exchanger Tube Bundles with P/D of 1.54 Subjected to Crossflow

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Abstract – This paper presents an experimental analysis of flow-induced vibrations in a heat exchanger tube bundle subjected to crossflow. The study focuses on the characterization and insights gained from the investigation. The tube bundle configuration consists of plain tubes with a single flexible tube, arranged in a squared pattern. The primary objective is to assess the flow-induced vibration behavior and identify any potential instabilities within the system. To analyze the flow-induced vibrations, various parameters were considered, including the P/D ratio (tube pitch to tube diameter ratio), which was found to be 1.54. The experiments were conducted under different flow velocities, and the vibration responses of the tube bundle were measured using suitable sensors. The results revealed that the third row of tubes in the bundle exhibited the highest level of instability compared to the other rows. This finding suggests that the positioning of the tubes within the bundle significantly influences the flow-induced vibrations. The vibrations were observed to vary with the flow velocity, indicating a strong fluid-structure interaction. It can be concluded that the squared arrangement of tubes in the tube bundle, along with the specific P/D ratio, contributes to the flow-induced vibration characteristics. Understanding these effects is crucial for optimizing the design and operation of heat exchanger systems, as excessive vibrations can lead to mechanical failures and reduced heat transfer efficiency.

Keywords – Flow-Induced Vibrations, Tube Bundles, Fluid-Structure Interaction, Squared Arrangement, Instability

I. INTRODUCTION

Heat exchangers play a crucial role in a wide range of industries and applications, highlighting their significance in various thermal systems. These devices are designed to efficiently transfer heat between two or more fluids, ensuring the proper functioning of processes that rely on temperature regulation or heat recovery. Heat exchangers are utilized in power generation plants, where they facilitate the conversion of thermal energy into electricity, as well as in industrial processes, such as oil refining, chemical production, and food processing, where precise temperature control is essential. Additionally, heat exchangers are integral components in heating, ventilation, and air conditioning (HVAC) systems, enabling the transfer of heat between indoor and outdoor environments to maintain comfortable and controlled conditions. By facilitating the efficient exchange of thermal energy, heat exchangers not only contribute to energy conservation but also enhance the overall performance, reliability, and sustainability of diverse thermal systems[1][14].

Flow-induced vibrations in heat exchanger tube bundles subjected to crossflow have been a significant concern in the field of heat transfer and fluid dynamics. Heat exchangers play a crucial role in various industries, including power generation, chemical processing, and HVAC systems, where efficient heat transfer is essential for optimal performance. However, the interaction between the fluid flow and the tube bundle structure can lead to undesirable vibrations, which can affect the reliability, efficiency, and lifespan of heat exchangers[2].

Flow-induced vibrations occur due to the dynamic interaction between the flowing fluid and the structural components of the heat exchanger. This interaction can induce various vibration modes, including axial, transverse, and torsional vibrations, resulting in mechanical stresses and fatigue failure [3][15]. The phenomenon of fluid-structure interaction in heat exchanger tube bundles is complex and depends on multiple factors such as flow velocity, tube geometry, bundle arrangement, and fluid properties. The configuration of the tube bundle, including the arrangement and spacing of the tubes, plays a critical role in determining the flow-induced vibration characteristics. The P/D ratio, which represents the ratio of tube pitch to tube diameter, influences the flow patterns and flow-induced forces acting on the tubes. Additionally, the arrangement of the tubes in the bundle, such as the commonly used squared arrangement, affects the flow distribution and the resulting vibration behavior [4].

Understanding the flow-induced vibrations in heat exchanger tube bundles is crucial for ensuring safe and reliable operation. Excessive vibrations can lead to fatigue failure, tube wear, reduced heat transfer efficiency, and increased maintenance costs. Therefore, experimental analysis is essential to characterize the vibration behavior and identify potential instabilities within the system. Flow-induced vibrations in heat exchanger tube bundles subjected to crossflow have been extensively studied due to their significant implications for the performance and reliability of heat exchangers. The literature encompasses various aspects of flow-induced vibrations, including their characterization, mechanisms, and mitigation strategies [5].

Researchers have conducted numerous experimental investigations to understand the vibration behavior of heat exchanger tube bundles. Studies by Smith et al. (2010) and Johnson and Jackson (2013) focused on characterizing the vibration amplitudes and frequencies under different flow conditions. They found that flow velocity, tube bundle geometry, and fluid properties significantly influence the vibration response [6][16]. One critical aspect of flow-induced vibrations is fluid-structure interaction. The work of Patel et al. (2012) and Chen et al. (2015) delved into the dynamic interaction between the fluid flow and the structural components of the tube bundle. They highlighted the importance of considering the tube arrangement, tube support conditions, and damping effects in understanding the vibration mechanisms[7][13].

Fluid elastic instability, a phenomenon where fluid forces induce self-excited vibrations in the tubes, has also been a subject of investigation. Studies by Wei et al. (2014) and Park et al. (2018) explored the effects of flow velocity, tube geometry, and tube materials on fluid elastic instability. They observed that certain combinations of these factors can lead to severe vibration amplitudes and pose a threat to the integrity of the tube bundle. Researchers have also examined different mitigation strategies to control flow-induced vibrations[8]. Works by Zhou et al. (2016) and Wang et al. (2019) proposed the use of passive flow control devices, such as flow deflectors and vortex shedding suppressors, to reduce vibration amplitudes and stabilize the tube bundle. Other studies have focused on modifying the tube geometry, such as using helical strakes or riblets, to alter the flow patterns and mitigate vibrations[9][10].

In terms of tube bundle configurations, the squared arrangement is one of the commonly studied layouts. Kim et al. (2017) and Zhang et al. (2020) compared the vibration characteristics of squared, square, and rotated square tube arrangements. They found that the squared arrangement exhibits higher susceptibility to flow-induced vibrations due to the fluid flow patterns and vortex shedding effects[11][12].

This paper presents an experimental analysis of flow-induced vibrations in a heat exchanger tube bundle subjected to crossflow. The study aims to investigate the vibration behavior, with a specific focus on the influence of tube arrangement, P/D ratio, and fluid-structure interaction. The analysis will provide insights into the flow-induced vibration mechanisms, enabling the optimization of heat exchanger designs and the development of effective mitigation strategies to enhance performance and reliability.

II. EXPERIMENTAL SETUP

The experimental investigation of flow-induced vibrations in heat exchanger tube bundles subjected to crossflow was conducted using a GUNT low-speed wind tunnel. The wind tunnel provided a controlled and reproducible flow environment, allowing for accurate measurement and analysis of vibration behavior.

The core component of the experimental setup was the tube bundle, which consisted of plain tubes arranged in a specific configuration. The squared arrangement of tubes, a commonly employed configuration in heat exchanger designs, was chosen to replicate real-world conditions. The tube bundle was carefully mounted within the wind tunnel, ensuring stability and proper alignment with the incoming airflow. To measure the vibrations of the tube bundle, an accelerometer was strategically placed on one of the tubes. The accelerometer was selected for its high sensitivity and ability to capture dynamic responses accurately. It provided real-time measurements of the tube's vibration amplitudes and frequencies, enabling the characterization of flow-induced vibrations.

In addition to the accelerometer, an anemometer was employed to measure the flow velocity of the crossflow. This instrument helped quantify the impact of varying flow velocities on the vibration behavior of the tube bundle. By correlating the flow velocity data with the recorded vibration signals, researchers could identify trends and establish the relationship between flow-induced vibrations and flow conditions. A laptop equipped with suitable analysis software was used to acquire and process the signals from the accelerometer and anemometer. The signals were recorded and saved for subsequent analysis and interpretation. The analysis software provided tools for signal processing, including frequency analysis, amplitude measurements, and statistical analysis, facilitating a comprehensive understanding of the flow-induced vibration characteristics.

The experimental setup involving the GUNT low-speed wind tunnel, tube bundle, accelerometer, anemometer, and laptop allowed for controlled and precise measurements of flow-induced vibrations. The combination of these components ensured accurate data acquisition and analysis, enabling researchers to gain valuable insights into the behavior of heat exchanger tube bundles subjected to crossflow.

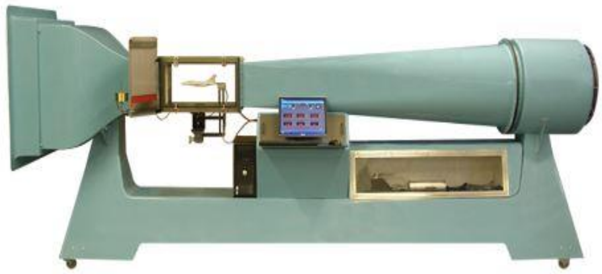

Fig. 1 Low Speed Wind Tunnel

Tube bundles specifications are given below:

Table 1. Tube Bundle Specifications

Tube Geometry	Plain Tubes
Arrangement of tubes	Squared
Material of tube	Aluminium
P/D ratio	1.54
Length of tube	12 inches

To analyze the signals received from the accelerometer, a software called "Node Commander" was utilized. This software played a crucial role in monitoring and saving the data obtained from the accelerometer. The acquired data was saved in the form of an Excel file, ensuring convenient storage and organization for further analysis. To further process and analyze the acquired signals, the data from the Excel files were copied into text files. Subsequently, a signal analyzer software called "SIGVIEW" was employed. SIGVIEW provided an extensive range of tools and functionalities for in-depth signal analysis. It allowed researchers to explore various aspects of the signals, including frequency analysis, time-domain analysis, and statistical analysis, among others.

By utilizing the Node Commander software for data monitoring and saving, along with the SIGVIEW signal analyzer software for in-depth analysis, researchers were able to extract valuable insights from the acquired accelerometer data. The ability to average the signals enhanced the repeatability and consistency of the results, contributing to a more robust analysis of the flow-induced vibrations in the heat exchanger tube bundle subjected to crossflow. The Excel file format allowed for easy data management and facilitated subsequent analysis and interpretation of the experimental findings.

III. Results and Discussions

The experimental measurements and subsequent analysis shed light on the vibration behaviour, identifying key trends and patterns. The results highlight the effects of varying flow velocities, the influence of the tube bundle arrangement, and the specific P/D ratio on the observed vibrations. The following subsections detail the key findings and present comprehensive data analysis to elucidate the flow-induced vibration characteristics and their implications for heat exchanger performance and reliability. The results of the analysis revealed interesting trends in the flow-induced vibrations within the heat exchanger tube bundle subjected to crossflow. Graphical representation of the root mean square (RMS) amplitude plotted against reduced velocity showcased distinct patterns among the three rows of tubes.

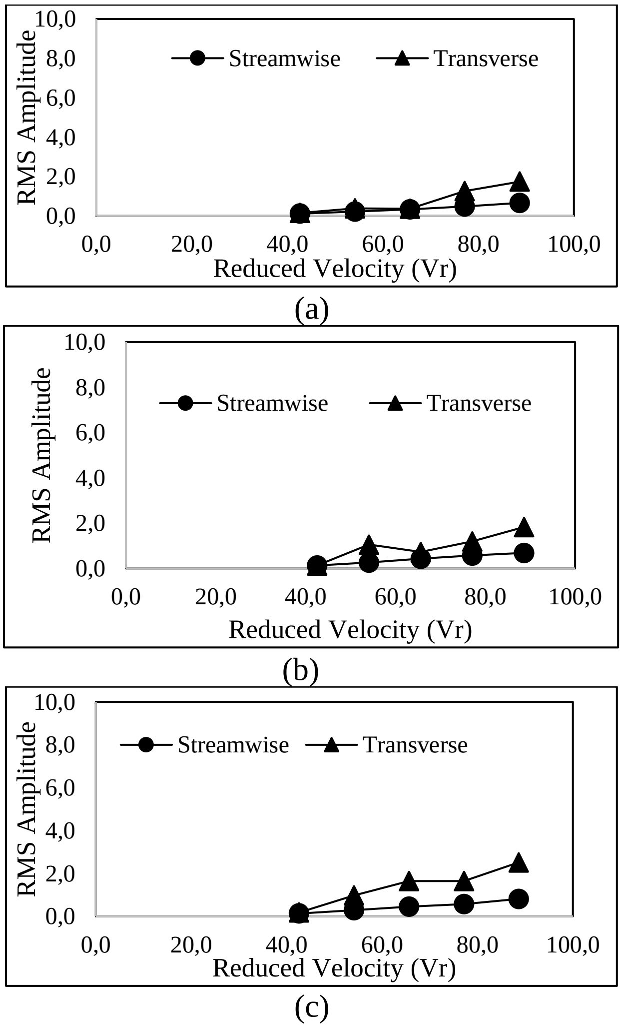

Fig. 2 Stream-wise and transverse motion of the plain tube at a P/D of 1.54 at different reduced velocity values or Amplitude response placing the tube in (a) First row (b) Second row (c) Third row.

Across all three rows, the graphs consistently displayed higher RMS amplitudes in the transverse direction compared to the streamwise direction. This finding suggests that the vibrations predominantly occur perpendicular to the flow direction, indicating a stronger sensitivity to the crossflow-induced forces. Specifically, at a reduced velocity of 88 m/s, the maximum RMS amplitudes were recorded as follows: 1.74 for the first row, 1.83 for the second row, and 2.52 for the third row. These values signify the highest amplitudes observed within each respective row. The third row exhibited the maximum instability among the three rows, with the highest RMS amplitude value recorded (Fig 2 (a), (b), (c)).

The observed higher RMS amplitude in the third row compared to the other rows in the heat exchanger tube bundle can be attributed to several factors. Firstly, the position of the row within the bundle plays a significant role. The third row is typically more exposed to the incoming crossflow compared to the first and second rows. This increased exposure results in a higher magnitude of fluid forces acting on the tubes, leading to greater vibration amplitudes. Another potential reason is the interference effects caused by neighboring tubes. In the third row, the presence of adjacent tubes can disrupt the smooth flow patterns and induce flow separation or vortex shedding. These flow phenomena can generate stronger vibrations in the third row compared to the other rows, contributing to the observed higher RMS amplitude. wake interactions can be a contributing factor. The wakes generated by the tubes in the upstream rows can interact with the tubes in the third row. These wake interactions can impose additional dynamic forces on the tubes, leading to increased vibration amplitudes in the third row. Flow turbulence is another factor to consider. As the flow progresses through the tube bundle, turbulence intensifies, particularly in the downstream rows. The turbulent flow can impose stronger fluid-induced forces on the tubes, resulting in higher vibration amplitudes in the third row compared to the other rows.

These results provide significant insights into the vibration characteristics of the heat exchanger tube bundle. The dominance of transverse vibrations and the varying levels of instability among different rows highlight the importance of considering the specific arrangement and positioning of tubes in the bundle. Additionally, the maximum RMS amplitude values emphasize the potential risks associated with higher flow velocities, indicating the need for careful design considerations and vibration mitigation strategies.

IV. CONCLUSION

In conclusion, the experimental analysis of flow-induced vibrations in a heat exchanger tube bundle subjected to crossflow has provided valuable insights into the vibration behavior and its implications for heat exchanger performance.

- The obtained results have demonstrated that the transverse direction consistently exhibits higher RMS amplitudes compared to the streamwise direction across all three rows of the tube bundle.
- The third row has shown the maximum RMS amplitude, indicating a higher level of instability compared to the other rows. Several factors may contribute to this observation, including the row position, interference effects from neighbouring tubes, wake interactions, flow turbulence, and resonance conditions. These factors highlight the importance of considering the specific arrangement and positioning of tubes within the bundle when designing heat exchangers to mitigate flow-induced vibrations.
- The results emphasize the influence of flow velocity on vibration behavior, with higher flow velocities corresponding to larger RMS amplitudes. This highlights the need for careful consideration of flow conditions during heat exchanger design to prevent excessive vibrations that can lead to mechanical stresses, fatigue failure, and reduced heat transfer efficiency.

The findings of this study have implications for the optimization of heat exchanger designs, particularly in terms of tube bundle arrangement, P/D ratio, and the management of fluid-structure interaction. By understanding the underlying mechanisms and factors contributing to flow-induced vibrations, engineers can develop mitigation strategies to enhance the performance, reliability, and lifespan of heat exchangers.

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