Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Experimental Study on The Performance of One-Directional and Bi-Directional Flow Conditions Across In-Line Tube Banks Heat Exchanger

Nurjannah Hasbullah[1,2], Fatimah Al Zahrah Mohd Saat[1,2,3,*], Fadhilah Shikh Anuar[2,4], Mohamad Firdaus Sukri[1,2], Mohd Zaid Akop[1,2], Zainuddin Abdul Manan[5]

[1] Fakulti Kejuruteraan Mekanikal (FKM), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2] Green and Efficient Energy Technology (GrEET), Centre for Advanced Research on Energy (CARe), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[3] Green Design & Manufacture Research Group, Centre of Excellence Geopolymer & Green Technology, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia
[4] Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan (FTKMP), Universiti Teknikal Malaysia Melaka (UTeM), Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[5] Process Systems Engineering Centre (PROSPECT), School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Johor, Malaysia

ARTICLE INFO

Article history:
Received 25 February 2022
Received in revised form 15 May 2022
Accepted 19 May 2022
Available online 17 June 2022

Keywords:
Heat transfer; tube banks; bi-directional flow; one-directional flow; thermoacoustics

ABSTRACT

The one-directional flow condition and the bi-directional flow condition are two flow conditions that can be found in many energy systems depending on the nature of the flow and the working mechanism of the system. This paper reports the differences in heat transfer performance for an in-line tube banks heat exchanger that is placed in the one-directional and the bi-directional flow conditions. The experiments involve the use of a blower as a flow inducer for one-directional flow while a loudspeaker with a constant frequency of 14.2 Hz is used as a flow inducer for bi-directional flow condition. A quarter wavelength resonator with 4 mm wall thickness and a length of 6600 mm was used in the investigation. The results of velocity and temperature were recorded using a hotwire anemometer and a type-K thermocouple, respectively. Results show that the behaviour of velocity and temperature in one-directional and the bi-directional flow conditions over an in-line heated tube banks are different with a maximum difference of 52 % for velocity and 79 % for temperature.

1. Introduction

Various types of compact heat exchangers have been created throughout the last century to perform as effective energy conversion technology. There are quite a number of heat exchangers (HE) utilized in industries in this century, and they are chosen based on their uses [1]. Fin and tube heat exchangers are examples of small heat exchangers that are frequently utilized in industries like for heating, ventilation, and air conditioning (HVAC) systems [2,3], naval and aerospace purposes [4], and also petrochemical industries [5]. Finned heat pipe and cooling pipe surrounding by fibers or

---

[*] *Corresponding author.*
E-mail address: fatimah@utem.edu.my

https://doi.org/10.37934/arfmts.96.2.7487

porous media are also used to enhance heat transfer performance of air conditioning system [6]. Flows around tube bundles with a large number of tubes, on the other hand, have been the subject of a great deal of experimental and numerical efforts. The in-line [7,8], staggered [9-11], rotating square [12], regular triangle [13,14], and parallel triangle [15] are a few of the array designs that were investigated by researchers. The worldwide waste heat recovery market is being boosted by thermal industries such as petrochemical plants. By 2019, it is expected to expand at a rate of 7.6 percent [16]. Refrigeration systems that use Cluoroflorocarbon (CFC) and Hydrofluorocarbons (HFC) have high coefficient of performance (COP) [17] but have a negative environmental impact [18]. Environmentally harmful refrigerants with high ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) must be replaced with environmentally friendly refrigerants [19]. These well-established technologies for refrigeration or cooling system involve the use of one-directional flow where the refrigeration cycles are completed with the use of mechanical equipment such as compressor [20], evaporator and condenser [21].

However, there are also some complex applications that do not involve the use of the usual one-directional flow condition, such as the condition in the blood flow [22,23] and the thermoacoustic cooler/generator [24,25]. Thermoacoustics use bi-directional flow of the acoustic wave to create the refrigeration or power cycles that resemble the cycles for thermodynamic process of a cooler and a generator [24]. The fluid in this complex system is flowing in bi-directional flow condition because the fluid flows back and forth in a cyclic nature. The difference between the one-directional and the bi-directional flows is as illustrated in Figure 1.

(a) (b)

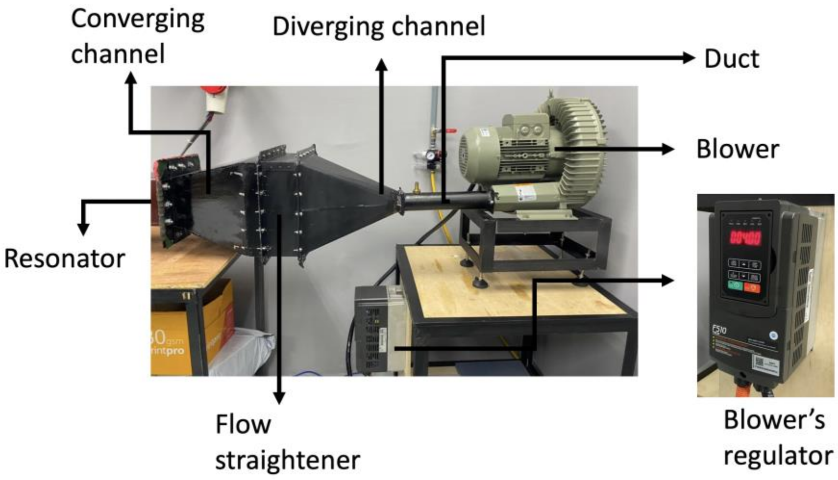
Fig. 1. Illustration of flow for the (a) one-directional and (b) bi-directional flow conditions

Another example is the ocean flow around the seawater heat exchanger that is submerged in the actual ocean. The fluid is fluctuating rather than a constant steady flow. Therefore, this situation can also be categorized as bi-directional flow condition. Because of the effect of temporal and spatial factors that cause periodic oscillations in this type of flow, oscillating flow analysis is more difficult than the steady flow analysis. The purpose of the current investigation is to evaluate the effect of changing flow conditions on heat transfer performance across tube banks through experimental investigations. Earlier investigations confirmed that the bi-directional flow exhibits different velocity and temperature behaviors across the staggered tube banks heat exchanger compared to that of the one-directional flow condition [10,26,27]. The numerical results as shown in ref [27] provided insights into fluid dynamics aspect that supplement the experimental findings of [10]. Mikheev *et al.,* carried out an experiment on the heat transfer performance of oscillating flow around a cylinder, and the findings showed that oscillation of an incoming flow might increase heat transfer [28]. With a few circumferential grooves inside heat exchanger tubes in a Stirling engine, Kuosa *et al.,* [29] explored the augmentation of heat transfer and pressure loss of oscillatory flow across the heat exchanger. The Stirling engine is a continuous external-combustion engine that may run on variety of fuels, including solar, geothermal, biomass, and industrial waste heat [30]. In comparison to conventional engines, the Stirling engine produces less pollution and has less incomplete combustion. As a result, the Stirling engine is seen as a key green energy device and a significant answer to the global warming problem [31]. Aside from that, thermoacoustic technology also offers green and sustainable solutions for at least two significant applications: cooling [32] and power production equipment [33]. Since the flow in this promising thermoacoustic energy technology is bi-directional in nature, it is therefore important to understand the heat transfer nature between the heat exchanger and the flow when it is placed in thermoacoustic environment. The heat transfer performances of tube banks with staggered arrangement under one-directional and bi-directional flow conditions were reported earlier [10]. The change of orientation of the tube banks changes the fluid dynamics of flow around the tube banks and therefore the heat transfer behavior is expected to be different too. Huang et. al. [34] stated that staggered arrangements were found to be more advantageous than the in-line arrangements for heat transfer but had a greater decrease in demand probably due to manufacturing difficulties. Similar observation was also reported in [35] but for different set of application. The different wake pattern and fluid dynamics behavior of flow across tube banks led to different heat transfer performance in these two orientations of tube banks [35]. The complexity is expected to be even more difficult to understand when pulsatile flow (another type of bi-directional flow condition) is involved [35]. In the analysis of complex nature of flow, it is common to start with simpler arrangement so that contribution to changes could be understood with minimum complexity [35, 36]. The investigation of [35] was done using computational method which means that the physics of flow and heat were solved with simplifications and assumptions. Understanding complex cases require physical experimental investigations and it is important that it is done by benchmarking the well-known flow condition. Hence, this paper reported the investigation of the effect of one-directional and bi-directional flows across an inline tube banks heat exchanger, which is a worthy addition to the results published by Hasbullah *et al.,* [10,27]. In this paper, the heat transfer and flow across an in-line heat exchanger will be shown.

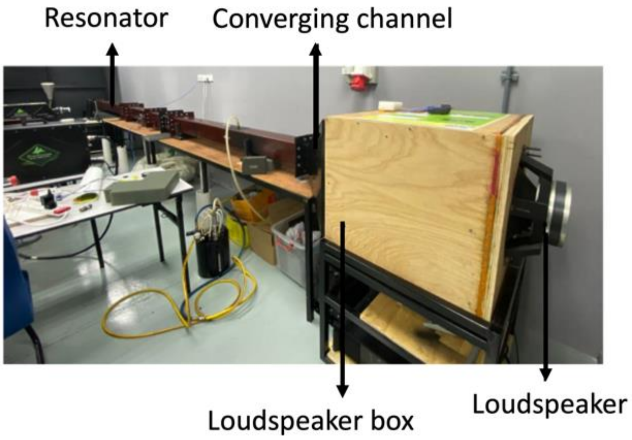
2. Experimental setup

As for different types of flow conditions (one-directional and bi-directional), the experiment was done by setting up the experimental work in order to study the heat transfer behavior for both flow conditions. Flow inducer is the important component in this study because it is used to produce air with a specific flow nature for the designated resonator. Each flow condition was obtained by using different type of flow inducers. The one-directional flow was created using a centrifugal blower (AIRSPEC ARC 269 (3)) and the bi-directional flow was induced by a loudspeaker (PD 1860). Figure 2 shows the experimental setup by using both the flow inducers.

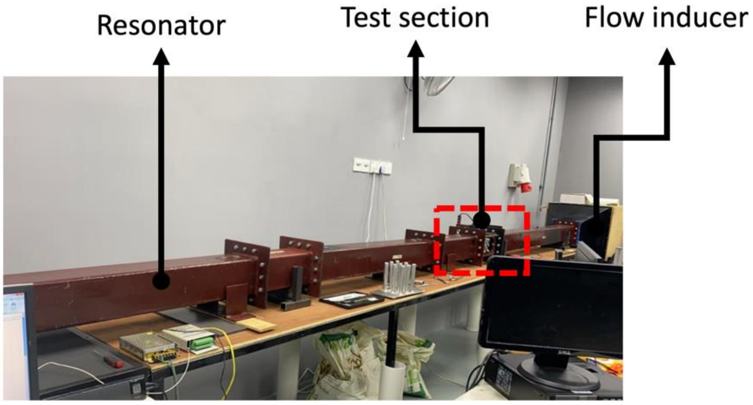
One-directional flow condition is controlled by the blower (AIRSPEC ARC 269 (3)) as a flow inducer. Based on Figure 2(a), the blower supplies air into the resonator through the duct, diverging channel, flow straightener and converging channel that are connected to each other and then be connected to the resonator. For this experiment, the end of the resonator was opened as the air flows in only one direction. Hence, when the blower is running the supplied air will flows through the length of the resonator and then leaves the resonator. However, for bi-directional flow condition, the setup is a bit different since it uses the loudspeaker (PD 1860) as a flow inducer as shown in Figure 2(b). In order to run the loudspeaker, the loudspeaker needs to be attached to the function generator (AFG 21005) and an amplifier (FLP-MT1201). Function generator is used to control the loudspeaker by setting up the input voltage while the frequency is kept at a constant value (14.2 Hz) which refers to the resonance frequency of the rig as reported in the earlier work [10,27].



(a) Setup for one-directional flow condition



(b) Setup for bi-directional flow condition



(c) Experimental rig

Fig. 2. Experimental setup for (a) the one-directional flow condition, (b) the bi-directional flow condition, and (c) the locations of resonator, test sections and flow inducer

For bi-directional flow condition, the end of the resonator is closed with a steel plate in order to create a standing wave bi-directional flow which complies with thermoacoustic's principle. The resonator is a hollow steel tube that is connected to the flow inducer and was designed to examine the standing wave thermoacoustic environment. This system is based on a thermoacoustic quarter wavelength criterion. The experimental setup consists of a 6.6 m long resonator connected to flow inducers: a blower, or a loudspeaker. The hollow resonator has a 4 mm wall thickness and a cross-sectional size of 142 mm x 142 mm. The test section that was shown in Figure 2(c) is where the tube banks heat exchanger was placed for the heat transfer study. Figure 3 shows the close-up diagram of the test section. There are nine tubes that are arranged in in-line configuration with transverse and horizontal lengths that are the same with distance of 45 mm between tubes. The tube banks heat exchanger is made of aluminium tubes with a diameter of 20 mm and a wall thickness of 3 mm. Although copper was traditionally utilised for heat exchangers, due to availability and convenience of production, aluminium was employed in this experiment. The choice of material will have no major influence on the convective heat transfer between the tube's surface and the external flow conditions since the experimental investigation is maintained at a constant surface temperature of 80°C. As a result, the use of aluminium in the current practice is justified.

The test segment is located at a location of 0.186 λ from the pressure antinode. For a quarter wavelength resonator, the pressure antinode is a position where the amplitude of pressure is at its highest level, and this happens at the end of the resonator. The wavelength, $\lambda = c/f$, where c is the speed of sound in air in m/s and f is the frequency in Hz, is theoretically calculated to be 24.15 m for this circumstance. As a result, the test area is located 4.5 m from the resonator's hard end. As shown in Figure 3, there are two hotwire anemometers (ST-732) which are located at the inlet and outlet of tube banks heat exchanger.

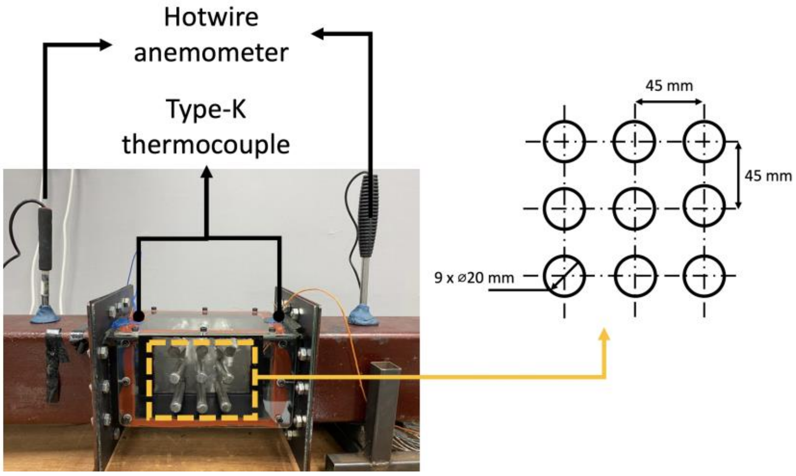
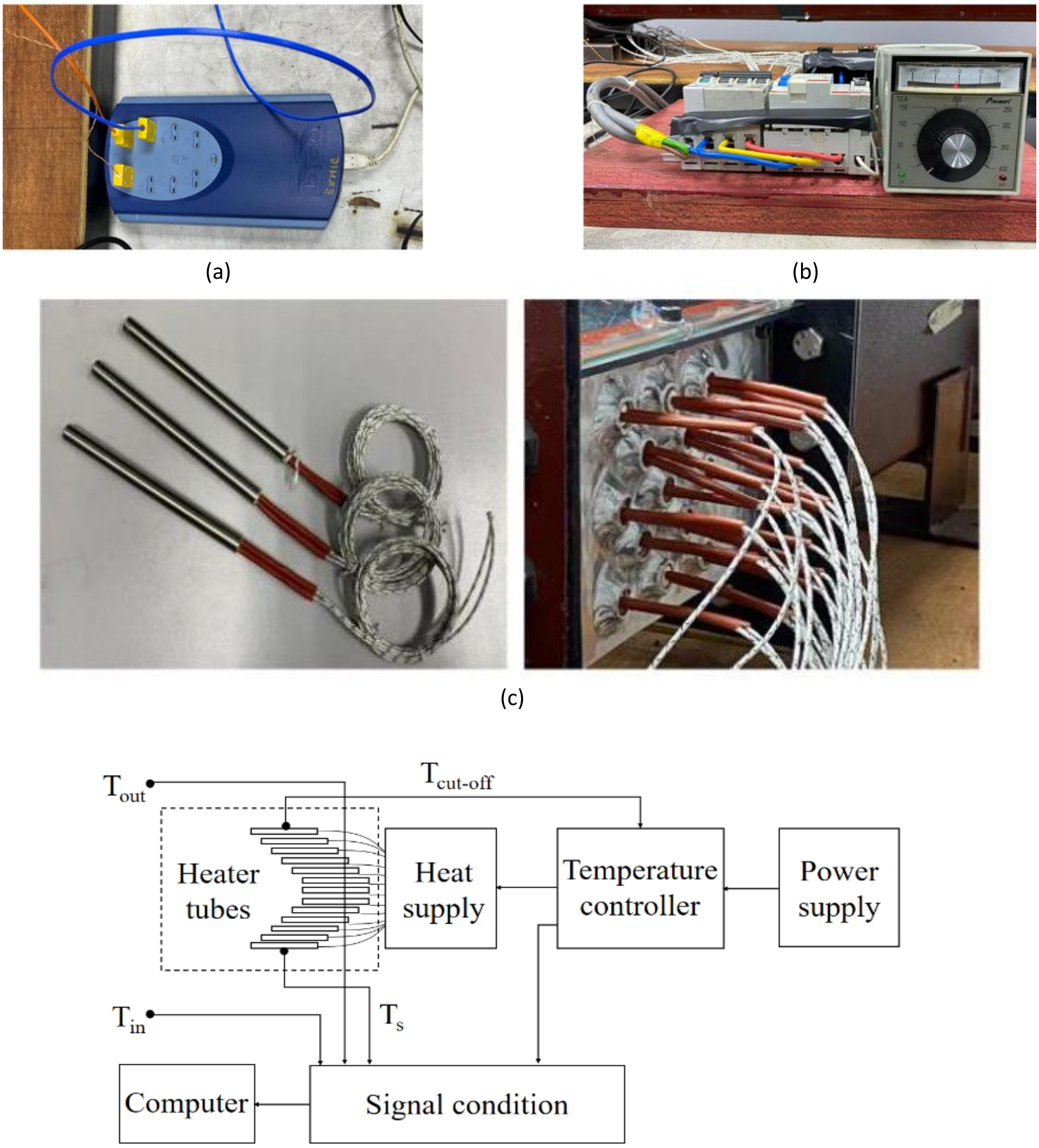


Fig. 3. In-line tube banks heat exchanger

Hotwire anemometer is placed at 270 mm from the center of the test section to the location of both left and right sides (right and left which are referred to as the inlet and outlet locations, respectively). The hotwire is used to measure the velocity of air that flows inside the resonator. In addition, the temperature is also measured in this experimental study by using a type-K thermocouple at both the locations of inlet and outlet of the test section. Another type-K thermocouple is placed on the surface of the tube and the thermocouple is connected to a Picolog signal conditioner (TC-08), as shown in Figure 4(a), to monitor the temperature of the tube. The signal from the signal conditioner is read and the data is saved in the computer. The other thermocouple is attached to the heater and is used to provide data for the cut-off circuit that controls the electric supply in order to maintain the surface temperature of the tube at a desired setting.

Figure 4(b) shows the heater controller system that was used in the experiment. Cylindrical heater cartridges, as shown in Figure 4(c), are inserted into the hollow part of the tube banks at the back side of the test section. The power supply to the heater cartridges is controlled by the heater controller system that is powered by a 64 Amp three phase power supply. The schematic diagram of the heating setup is as shown in Figure 4(d).



(a) (b)

(c)

(d)

Fig. 4. (a) Picolog TC-08 signal conditioner, (b) tube bank's heater controller, (c) cylindrical heater cartridge [10] and (d) the schematic diagram of the heater tubes connection [10]

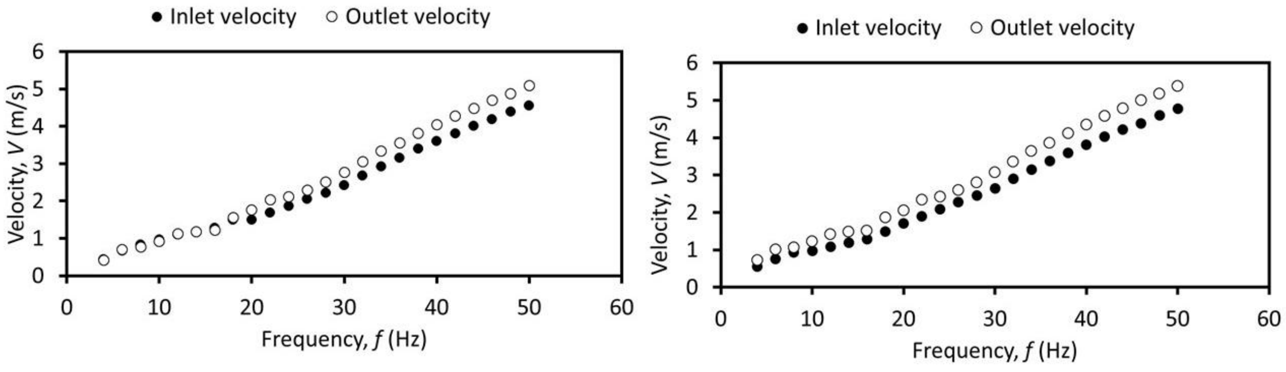
The experiment was done with tube banks heat exchanger that was heated to 40°C and 80°C. The two heated conditions were tested for two different flow conditions: the one-directional and the bi-directional flows. Due to the limitation of the measurement instrumentations, data can only be collected for flow with tube banks set at a maximum of 80°C.

3. Results

3.1 Velocity Changes Across Tube Banks Heat Exchanger

The experimental results were collected by investigating the velocity of flow inside the resonator for one-directional and bi-directional flow conditions. As stated earlier, the experiments involved the use of two different flow inducers: the loudspeaker and the blower. For the data comparison between both flow conditions, the hotwire anemometer which was used to measure the velocity is placed at the inlet and outlet locations of the tube banks heat exchanger. The same locations of hotwire were used when running different type of flow inducers. Tube banks heat exchanger was heated at 40°C and 80°C, and the changes to the fluid's flow and temperature inside the resonator were observed. The results are shown in Figure 5. The one-directional flow condition's experimentations were done by using a centrifugal blower as a flow inducer. The blower's frequency is set to change from the minimum input setting of 4 Hz until the maximum setting of 50 Hz. These values were selected because of the limitation of the blower and the experimental rig. With the maximum frequency of 50 Hz, it is found that the velocity in the resonator tube tunnel, when the tubes are heated to surface temperatures of 40°C and 80°C, reached a maximum value of 5.08 ± 0.02 m/s and 5.38 ± 0.02 m/s, respectively. The results showed in Figure 5(a) is the data of velocity changes as the input frequency of the blower changes for one-directional flow conditions with tubes heated at 40°C. The increasing trend of the velocity is observable when the frequency is increasing. The trend of velocity changes at inlet and outlet measurement locations is almost the same with very little differences during the low flow amplitude region when flow is induced by the centrifugal blower working in the range of 4 Hz to 18 Hz. This is because of the low frequency that is induced by the blower and when the input is low, the velocity of air inside the resonator is small. The velocity of flow during this low frequency supply region is between 0.42 ± 0.01 m/s and 1.27 ± 0.01 m/s. However, at 18 Hz and onwards, the trend changes as the outlet velocity becomes higher than the inlet velocity. The difference between the velocity at inlet and outlet locations becomes bigger as the blower supply flow at higher frequencies. The largest difference can be seen at 50 Hz with the inlet velocity of 4.56 ± 0.02 m/s and an outlet velocity of 5.08 ± 0.02 m/s. The difference between them is 0.53 m/s. This small range of differences indicate that the velocity at the upstream and downstream locations of the tube banks heat exchanger are almost the same.

Figure 5(b) presents the result of velocity changes for one-directional flow condition over tube banks that are heated at 80°C. The trend of velocity changes with the changes of input flow frequency is very much similar to the case presented in Figure 5(a) except that the disparity between the velocity at the inlet and outlet locations are seen to start taking place earlier. The velocity of flow at the two measured locations are different even when the blower is running at a very low frequency of 4 Hz. The velocity value at inlet and outlet positions are recorded to be at 0.56 ± 0.03 m/s and 0.72 ± 0.005 m/s, respectively. This gives a difference of 0.61 m/s between the flow at inlet and outlet locations. This is the effect of heat. When tubes are heated to higher temperature, the fluid is hotter and therefore lighter to travel to larger distance. As a result, the velocity of flow becomes different at locations before and after the heater. The differences become wider as the blower frequency increases. At 50 Hz which is at high frequency, the outlet location is at a maximum velocity of 5.38 ± 0.02 m/s while the inlet velocity is at 4.77 ± 0.01 m/s. The difference between the inlet and outlet velocities at 50 Hz flow input is 0.61 m/s. In general, Figure 5(a) and (b) show that as the blower's frequency is increasing the difference between the velocity at locations of upstream and downstream of the heated tube banks becomes bigger.



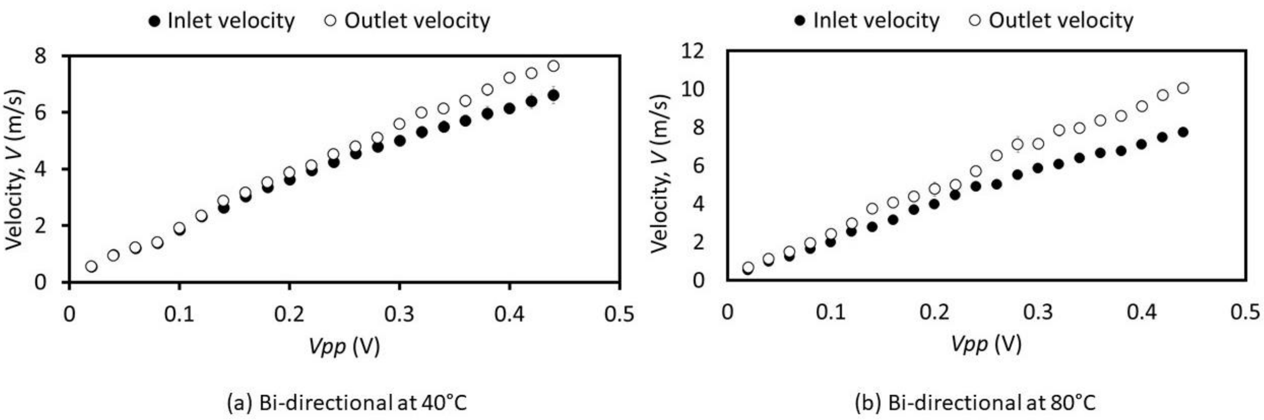
(a) One-directional at 40°C

(b) One-directional at 80°C

Fig. 5. Velocity changes across an in-line tube banks heat exchanger in one-directional flow condition for tubes that are heated at (a) 40°C and (b) 80°C

Figure 6 shows the results of velocity changes for bi-directional flow condition across an in-line tube banks heat exchanger at 40°C and 80°C. The air flow inside the resonator is induced by a loudspeaker. The air flow that is generated by the loudspeaker flows to the left during the first half of the cycle and then reverse to the right during the second half of the cycle to complete a full one cycle of bi-directional flow [27]. The flow repeats at a pace that depends on the resonance frequency of the flow. The amplitude of the bi-directional flow is set using the function generator through the change of input for peak-to-peak velocity, V_{pp}, that ranges from a minimum value of 0.02 V to a maximum of 0.44 V. It is interesting to note that the loudspeaker can generate a high amplitude of velocity inside the resonator with a maximum value of 10.06 ± 0.1 m/s at 0.44 V of input velocity. The same trend of velocity changes with input changes can be seen for the one-directional flow condition as was discussed for Figure 5, where the velocity is increasing as the peak-to-peak input voltage (V_{pp}) is increasing. However, the difference between the inlet and outlet velocities for the bi-directional flow cases is larger compared to that of the one-directional flow and the difference increases as the V_{pp} is increasing.

At the beginning, the inlet velocity was found slightly higher than the outlet velocity. Nevertheless, when flow is induced at 0.14 V for both the conditions of tubes (heated at 40°C and 80°C), the difference between velocities at both locations are observable and becomes more significant. For both the tubes temperature of 40°C and 80°C, the maximum velocity value was recorded at the outlet location and the value is 7.643 ± 0.17 m/s and 10.06 ± 0.07 m/s, respectively. The value shows that when the temperature increases, the velocity also increases as the kinetic energy of the fluid flow is high. For bi-directional flow, the maximum difference between velocity at inlet and outlet locations was found for flow that is induced by a peak-to-peak voltage supply of 0.44 V where the inlet velocity is 7.73 ± 0.07 m/s while the maximum outlet velocity is 10.06 ± 0.07 m/s, as presented in Figure 6(b).



(a) Bi-directional at 40°C

(b) Bi-directional at 80°C

Fig. 6. Velocity changes across an in-line tube banks heat exchanger in bi-directional flow condition when tubes are heated at (a) 40°C and (b) 80°C

Comparing both flow conditions, one-directional and bi-directional flows, the highest velocity that can be offered by the loudspeaker is 10.06 ± 0.07 m/s but the highest velocity that can be achieved when blower is used is only at 5.38 ± 0.02 m/s. For the purpose of comparing results between the two flow conditions, the experiment is then conducted following the maximum setting of the blower where the input velocity within the resonator is expected to be at approximately 4.7 m/s. The difference between values of velocity at inlet and outlet locations of bi-directional flow environment is to be expected for standing wave thermoacoustic environment. In the quarter wavelength setup, the velocity amplitude is higher near the input and should be lower towards the other end of the resonator. Hence, the velocity at outlet location is theoretically lower than that of the inlet location. However, the presence of heated tube banks seems to alter the condition a bit, probably due to the presence of flow induced by heat. As the input voltage increases, the difference becomes bigger.

3.2 Temperature Difference Across Tube Banks Heat Exchanger

Both flow conditions were experimentally tested for input velocity that ranges up to approximately 4.7 – 5.0 m/s and the velocity and temperature of the air inside the resonator at the inlet and outlet locations across the in-line tube banks heat exchanger are recorded. Figure 7 shows the temperature difference of one-directional and bi-directional flow conditions across the in-line tube banks heat exchanger when the tube is set to be at 40°C and 80°C as shown in (a) and (b), respectively. The pattern of the temperature of fluid that flows in one-directional flow condition across the heated tube bank was found decreasing when the input velocity is increasing. The tube banks heat exchanger was set to 40°C and 80°C, and as expected the temperature of air at the inlet and outlet locations are lower than the temperature that was set at the heated tube. In heat transfer, the temperatures of fluid that flows over the surface are important parameters to be considered [37]. Figure 7 shows the temperature different of air between inlet and outlet locations of the tube banks heat exchanger when it is placed in one-directional flow and bi-directional flow conditions. The difference of temperature between the inlet and outlet locations are observed for the two tested flow conditions. At tube temperature of 40°C, the fluid’s temperature difference between the locations of inlet and outlet is as shown in the Figure 7(a). The temperature difference for one-directional flow condition is higher than that of the bi-directional flow condition. The pattern of temperature difference of one-directional flow shows that as the velocity is increasing, the temperature difference slowly decreasing and then becoming stable or consistent at almost a constant value. For tube that was heated at 40°C, the highest temperature difference was recorded to be 16.23 ± 0.64 °C for one-directional flow when the flow was induced at low input frequency of 4 Hz. For bi-directional flow, the highest value was seen at an input of 0.02 V with value of 4.67 ± 0.53 °C. As the velocity is increasing, the temperature difference becomes almost constant at a low value of approximately 8.62 ± 0.46 °C for one-directional and 0.39 ± 0.21 °C for bi-directional flow condition.

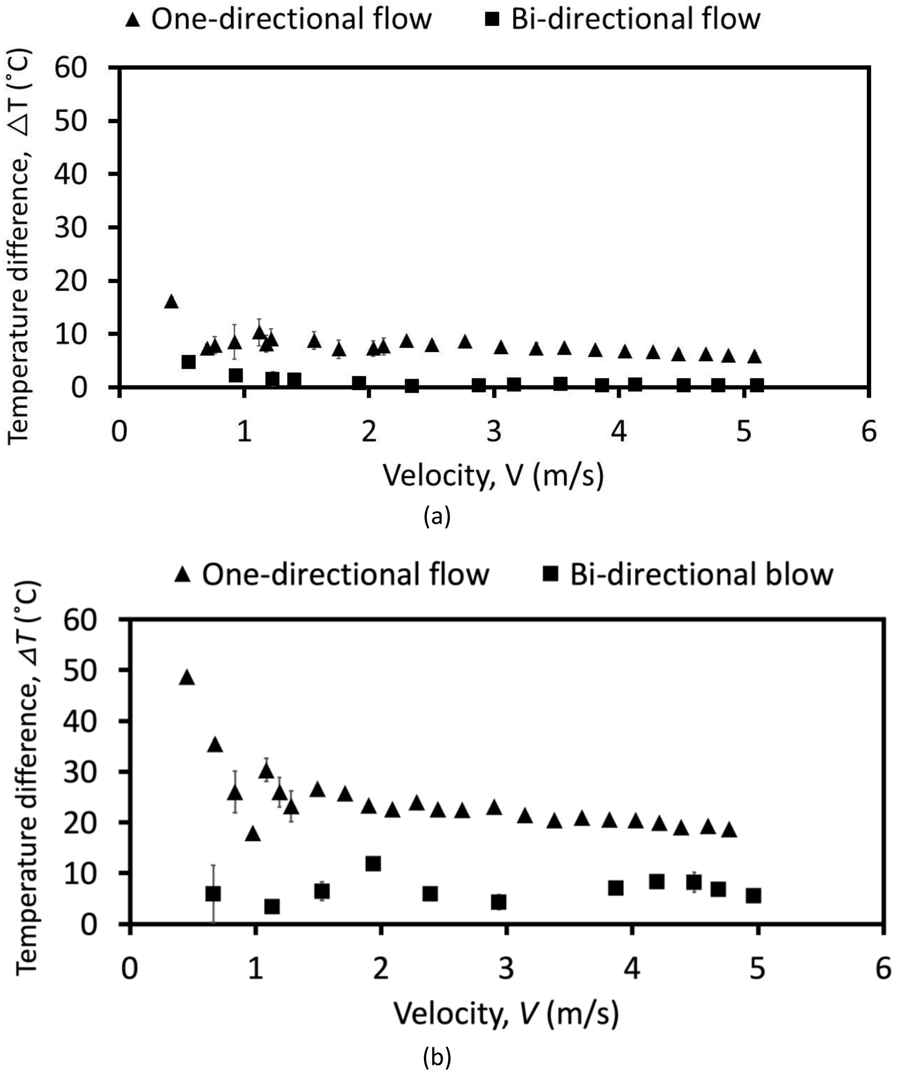


Fig. 7. Temperature difference for one-directional and bi-directional flow conditions when the tube is heated at (a) 40°C and (b) 80°C

Figure 7(b) shows the result of temperature difference against velocity for both the tested flow conditions when tubes are heated at 80°C. For the one-directional flow condition at low flow amplitude of 0.5 m/s, the temperature difference between the inlet and outlet locations is still high with the difference of 48.00 ± 0.37 °C but as the velocity is increasing, the temperature difference is decreasing and then started to achieve a stable constant condition when the flow is between 1.5 m/s until 4.77 m/s. At lower velocity, the natural convection is higher than that at the high velocity. This could lead to a large difference of the temperature value. Nevertheless, as the velocity is higher, the natural convection become weaker and forced convection is bigger. When this happens, heat is distributed more evenly within then air. As a result, little difference of temperature value is observed between the inlet and outlet locations of the tube banks heat exchanger.

Based on Figure 7, the temperature difference for bi-directional flow condition can be seen to be consistently small for cases with tubes heated at 40°C and 80°C. The reason behind that is because of the oscillating condition of air when it flows in bi-directional condition inside the resonator. The hard end of the resonator was sealed so that it allowed the air to flow back and forth across the tube banks in standing wave condition. Because of that, the temperature difference between both the inlet and outlet locations stay small as the air at upstream and downstream locations are equally heated as fluid oscillates across the structure. A bigger temperature difference is recorded for air that flows in one-directional condition across the tube banks heat exchanger. In one-directional flow, the heated air travels in one-way only. As a result, the downstream air flows with higher temperature compared to the upstream air. Hence, significant temperature difference is observed. At low range of flow amplitude, the drastic change of temperature difference may be related to the developing region and the flow becomes fully developed as the velocity increases above 2 m/s. The distinct difference between the temperature change at upstream and downstream locations of the one-directional and the bi-directional flow conditions indicate that the fluid dynamics and heat transfer between the two flow conditions are different. Hence, a more comprehensive investigations are needed to establish a more concrete foundations for the analysis of heat transfer of the less known bi-directional flow condition.

4. Conclusions

Experimental investigations of one-directional and bi-directional flow conditions across an in-line tube banks heat exchanger were studied with the use of different flow inducers: blower and loudspeaker. The results of the study can be concluded as follows

i. For input flow that ranges up to 5 m/s, the inlet and outlet velocity of the air in one-directional and bi-directional flow conditions across heated in-line tube banks are different. The range of velocity difference for bi-directional flow condition was recorded to be between 19 % and 25 % and for the one-directional flow condition the differences were within the range of 12 % to 18 %. The upstream and downstream velocity of air are almost the same for one-directional flow, but different values were observed when the bi-directional air of a standing wave nature flows over the heated tube banks.

ii. Different pattern of temperature difference for each flow condition is observed due to the different nature of the flow. The decreasing pattern of the one-directional flow condition at low flow amplitude was related to the developing nature of flow within that region. After 2 m/s, flow becomes fully developed and an almost constant data was recorded when input velocity is increasing. However, for bi-directional flow conditions, the temperature difference is fluctuated at an almost constant low value due to back-and-forth directions of flow. Temperature difference for one-directional flow was found to be higher than that of the bi-directional flow conditions by a maximum of 79 % difference.

iii. For the investigated cases that are bounded by tubes temperature that ranges from 40°C to 80°C, it can be concluded that the different tube temperature gives exactly the same pattern of results but with different amplitude. At 40°C, the velocity changes between inlet and outlet locations are not big (10 % difference for one-direction and 15 % for bi-directional flow conditions). While at 80°C, the velocity changes between both the inlet and outlet locations can be seen clearly as it become wider and the differences are recorded to be by 12 % and 23 % for one-directional and bi-directional conditions, respectively. This behavior can also be seen for temperature difference. As the tube temperature is increasing, the difference of temperature between the inlet and outlet locations is also increasing with an average of differences recorded to be about 80%.

Apparently, temperature and velocity at different locations, such as the inlet and outlet, are critical factors in determining the heat transfer performance for each flow states. In regards of the trend of changes in velocity and temperature, the one-directional and bi-directional flow conditions, according to the findings of the current experimental investigations, are not showing comparable behaviours. More investigations are needed to gather comprehensive understanding about the impact of flow conditions on heat transfer between fluid and heat exchangers.

Acknowledgement

We would like to acknowledge Ms. Chou Aw Lin for providing supplementary experimental data for bi-directional flow tests of 40°C tubes. This research was done using facilities at Universiti Teknikal Malaysia Melaka and the works are funded by the Ministry of Higher Education Malaysia (FRGS/1/2021/FKM-CARE/F00434). Part of the work was initially accepted and presented at ICESEAM2021.

References

[1] Nair, G. Sashwin, Ahmed N. Oumer, Azizuddin Abd Aziz, and Januar Parlaungan Siregar. "Flow and Heat Transfer Simulation Analysis of 3D Compact Heat Exchanger." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 88, no. 3 (2021): 71-87. https://doi.org/10.37934/arfmts.88.3.7187

[2] Matos, R. S., J. V. C. Vargas, M. A. Rossetim, M. V. A. Pereira, D. B. Pitz, and J. C. Ordonez. "Performance comparison of tube and plate-fin circular and elliptic heat exchangers for HVAC-R systems." *Applied Thermal Engineering* 184 (2021): 116288. https://doi.org/10.1016/j.applthermaleng.2020.116288

[3] Liu, Miaomiao, Carlos Jimenez-Bescos, and John Calautit. "CFD investigation of a natural ventilation wind tower system with solid tube banks heat recovery for mild-cold climate." *Journal of Building Engineering* (2021): 103570. https://doi.org/10.1016/j.jobe.2021.103570

[4] Li, Nan, Yun Zhao, Hao Wang, Qiao Chen, Zhe Li, Yuan Ma, and Guihua Tang. "Thermal and hydraulic performance of a compact precooler with mini-tube bundles for aero-engine." *Applied Thermal Engineering* 200 (2022): 117656. https://doi.org/10.1016/j.applthermaleng.2021.117656

[5] Mousavi, Seyed Mohammad, Omid Ali Akbari, Ghanbarali Sheikhzadeh, Ali Marzban, Davood Toghraie, and Ali J. Chamkha. "Two-phase modeling of nanofluid forced convection in different arrangements of elliptical tube banks." *International Journal of Numerical Methods for Heat & Fluid Flow* (2019). https://doi.org/10.1108/HFF-10-2018-0599

[6] Evi Sofia, Nandy Putra, B. Ali Gunawan. "Evaluation of indirect evaporative cooling performance integrated with finned heat pipe and Luffa Cylindrica Fiber as Cooling/Wet Media." *Journal of Advanced Research in Experimental Fluid Mechanics and Heat Transfer* 3, no. 1 (2021): 16-25.

[7] Abed, Nabeel, and Imran Afgan. "A CFD study of flow quantities and heat transfer by changing a vertical to diameter ratio and horizontal to diameter ratio in inline tube banks using URANS turbulence models." *International Communications in Heat and Mass Transfer* 89 (2017): 18-30. https://doi.org/10.1016/j.icheatmasstransfer.2017.09.015

[8] Niemelä, Niko Pietari, Antti Mikkonen, Kaj Lampio, and Jukka Konttinen. "Computational Fluid Dynamics Based Approach for Predicting Heat Transfer and Flow Characteristics of Inline Tube Banks with Large Transverse Spacing." *Heat Transfer Engineering* 42, no. 3-4 (2021): 270-281. https://doi.org/10.1080/01457632.2019.1699294

[9] Yilmaz, Alper, Mehmet Tahir Erdinç, and Tuncay Yilmaz. "Optimization of crossflow staggered tube banks for prescribed pressure loss and effectiveness." *Journal of Thermophysics and Heat Transfer* 31, no. 4 (2017): 878-888. https://doi.org/10.2514/1.T5033

[10] Hasbullah, Nurjannah, Fatimah Al Zahrah Mohd Saat, Fadhilah Shikh Anuar, Dahlia Johari, and Mohamad Firdaus Sukri. "Temperature and Velocity Changes Across Tube Banks in One-directional and Bi-directional Flow Conditions." *Evergreen* (2021): 428-437. https://doi.org/10.5109/4480725

[11] Nur Marissa Kamarul baharin, Mohd Azan Mohammed Sapardi, Nur Nadhirah Ab Razak, Ahmad Hussein Abdul Hamid, Syed Noh Syed Abu Bakar. "Study on Magnetogydrodynamic Flow Past Two Circular Cylinders in Staggered Arrangement." *CFD Letters* 13, no. 11 (2021): 65-77. https://doi.org/10.37934/cfdl.13.11.6577

[12] Mikhailenko, S. A., M. A. Sheremet, and A. A. Mohamad. "Convective-radiative heat transfer in a rotating square cavity with a local heat-generating source." *International Journal of Mechanical Sciences* 142 (2018): 530-540. https://doi.org/10.1016/j.ijmecsci.2018.05.030

[13] Wang, Wen, and Edward J. Bissett. "Frictional and heat transfer characteristics of flow in triangle and hexagon channels of wall-flow monoliths." *Emission Control Science and Technology* 4, no. 3 (2018): 198-218. https://doi.org/10.1007/s40825-018-0093-7

[14] Wang, Qifan, Minxia Li, Wenjie Xu, Liang Yao, Xuetao Liu, Dandan Su, and Pai Wang. "Review on liquid film flow and heat transfer characteristics outside horizontal tube falling film evaporator: Cfd numerical simulation." *International Journal of Heat and Mass Transfer* 163 (2020): 120440. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120440

[15] Yu, Chulin, Jian Chen, Min Zeng, and Bingjun Gao. "Numerical study on turbulent heat transfer performance of a new parallel-flow shell and tube heat exchanger with sinusoidal wavy tapes using RSM analysis." *Applied Thermal Engineering* 150 (2019): 875-887. https://doi.org/10.1016/j.applthermaleng.2019.01.043

[16] Lotfi, Babak, and Bengt Sundén. "Development of new finned tube heat exchanger: Innovative tube-bank design and thermohydraulic performance." *Heat Transfer Engineering* 41, no. 14 (2020): 1209-1231. https://doi.org/10.1080/01457632.2019.1637112

[17] Li, Hua, Seok-Kwon Jeong, and Sam-Sang You. "Feedforward control of capacity and superheat for a variable speed refrigeration system." *Applied Thermal Engineering* 29, no. 5-6 (2009): 1067-1074. https://doi.org/10.1016/j.applthermaleng.2008.05.022

[18] Das, Krishnendu, K. Sivasami, S. Majumder, and N. Das. "Studies of Impact on Environment Due to E-Waste and Refrigeration Waste During Ship Recycling Process in India-A Way Out." *ISFIRE Working Paper Series (ISSN NO: 2454-5597)* 40 (2021). https://doi.org/10.1201/9781003202240-62

[19] Akbar, Ronald, Jong Taek Oh, and Agus Sunjarianto Pamitran. "Evaluation of Heat Transfer Coefficient of Two-Phase Flow Boiling with R290 in Horizontal Mini Channel." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 88, no. 3 (2021): 88-95. https://doi.org/10.37934/arfmts.88.3.8895

[20] Sleiti, Ahmad K., Mohammed Al-Khawaja, and Wahib A. Al-Ammari. "A combined thermo-mechanical refrigeration system with isobaric expander-compressor unit powered by low grade heat–Design and analysis." *International Journal of Refrigeration* 120 (2020): 39-49. https://doi.org/10.1016/j.ijrefrig.2020.08.017

[21] Li, Zhaohua, Kun Liang, and Hanying Jiang. "Experimental study of R1234yf as a drop-in replacement for R134a in an oil-free refrigeration system." *Applied Thermal Engineering* 153 (2019): 646-654. https://doi.org/10.1016/j.applthermaleng.2019.03.050

[22] Krishna, M. Veera, B. V. Swarnalathamma, and J. Prakash. "Heat and mass transfer on unsteady MHD Oscillatory flow of blood through porous arteriole." In *Applications of Fluid Dynamics*, pp. 207-224. Springer, Singapore, 2018 https://doi.org/10.1007/978-981-10-5329-0_14

[23] Thineshwaran Subramaniam, Mohammad Rasidi Rasani. "Pulsatile CFD numerical simulation to investigate the effect of various degree and position of stenosis on carotid artery hemodynamics." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 26, no. 2 (2022): 29-40. https://doi.org/10.37934/araset.26.2.2940

[24] Chen, Geng, Yufan Wang, Lihua Tang, Kai Wang, and Zhibin Yu. "Large eddy simulation of thermally induced oscillatory flow in a thermoacoustic engine." *Applied Energy* 276 (2020): 115458. https://doi.org/10.1016/j.apenergy.2020.115458

[25] Alamir, Mahmoud A. "Thermoacoustic energy conversion devices: Novel Insights." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 77, no. 2 (2020): 130-144. https://doi.org/10.37934/arfmts.77.2.130144

[26] Wu, Zhenjing, Shijun You, Huan Zhang, and Wandong Zheng. "Experimental investigation on heat transfer characteristics of staggered tube bundle heat exchanger immersed in oscillating flow." *International Journal of Heat and Mass Transfer* 148 (2020): 119125. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119125

[27] Hasbullah, Nurjannah, Fatimah Al Zahrah Mohd Saat, Fadhilah Shikh Anuar, Mohamad Firdaus Sukri, and Patcharin Saechan. "Experimental and numerical studies of one-directional and bi-directional flow conditions across tube banks heat exchanger." *Thermal Science and Engineering Progress* 28 (2022): 101176. https://doi.org/10.1016/j.tsep.2021.101176

[28] Mikheev, N. I., V. M. Molochnikov, A. N. Mikheev, and O. A. Dushina. "Hydrodynamics and heat transfer of pulsating flow around a cylinder." *International Journal of Heat and Mass Transfer* 109 (2017): 254-265. https://doi.org/10.1016/j.ijheatmasstransfer.2017.01.125

[29] Kuosa, Maunu, Kari Saari, Ari Kankkunen, and T-M. Tveit. "Oscillating flow in a stirling engine heat exchanger." *Applied Thermal Engineering* 45 (2012): 15-23. https://doi.org/10.1016/j.applthermaleng.2012.03.023

[30] Nik Kechik Mujahidah Nik Abdul Rahman, Syamimi Saadon, mohd Hasrizam Che Man. "Waste Heat Recovery of Biomass Industrial Boilers by Using Stirling Engine." *Journal of Advanced Research in Applied Mechanics* 81, no. 1 (2021): 1-10. https://doi.org/10.37934/aram.81.1.110

[31] Xin, Feng, Zhichun Liu, Si Wang, and Wei Liu. "Study of heat transfer in oscillatory flow for a Stirling engine heating tube inserted with spiral spring." *Applied Thermal Engineering* 143 (2018): 182-192. https://doi.org/10.1016/j.applthermaleng.2018.07.071

[32] Gökay, İlker, and Rasim Karabacak. "Experimental investigation of the effect of different waveforms on heat transfer in a thermoacoustic cooler." *International Journal of Refrigeration* (2021). https://doi.org/10.1016/j.ijrefrig.2021.04.015

[33] Wang, Kai, Swapnil Dubey, Fook Hoong Choo, and Fei Duan. "Thermoacoustic Stirling power generation from LNG cold energy and low-temperature waste heat." *Energy* 127 (2017): 280-290. https://doi.org/10.1016/j.energy.2017.03.124

[34] Huang, Szu-Chi, Chen-Chih Wang, and Yao-Hsien Liu. "Heat transfer measurement in a rotating cooling channel with staggered and inline pin-fin arrays using liquid crystal and stroboscopy." *International Journal of Heat and Mass Transfer* 115 (2017): 364-376. https://doi.org/10.1016/j.ijheatmasstransfer.2017.07.040

[35] Blackall, James L., Hector Iacovides, and Juan C. Uribe. "Modeling of in-line tube banks inside advanced gas-cooled reactor boilers." *Heat Transfer Engineering* 41.19-20 (2020): 1731-1749. https://doi.org/10.1080/01457632.2019.1640486

[36] Allafi, Waleed Almukhtar, Fatimah Al Zahrah Mohd Saat, and Xiaoan Mao. "Fluid dynamics of oscillatory flow across parallel-plates in standing-wave thermoacoustic system with two different operation frequencies." *Engineering Science and Technology, an International Journal* 24, no. 1 (2021): 41-49. https://doi.org/10.1016/j.jestch.2020.12.008

[37] Lin, Chou Aw, Fatimah Al-Zahrah Mohd Sa'at, Fadhilah Shikh Anuar, Mohamad Firdaus Sukri, Mohd Zaid Akop, and Zainuddin Abdul Manan. "Heat Transfer Across Tube Banks with a Passive Control Vortex Generator in Steady One-Directional and Oscillatory Flows." *CFD Letters* 13, no. 1 (2021): 1-18. https://doi.org/10.37934/cfdl.13.1.118