Internally Heated Screw Pyrolysis Reactor (IHSPR) 
heat transfer performance study

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Abstract. 1.5 billion end-of-life tyres (ELT) were discarded globally each year and pyrolysis is considered the best solution to convert the ELT into valuable high energy-density products. Among all pyrolysis technologies, screw reactor is favourable. However, conventional screw reactor risks plugging issue due to its lacklustre heat transfer performance. An internally heated screw pyrolysis reactor (IHSPR) was developed by local renewable energy industry, which serves as the research subject for heat transfer performance study of this particular paper. Zero-load heating test (ZLHT) was first carried out to obtain the operational parameters of the reactor, followed by the one dimensional steady-state heat transfer analysis carried out using SolidWorks Flow Simulation 2016. Experiments with feed rate manipulations and pyrolysis products analyses were conducted last to conclude the study.

1. Introduction
The surging population size and the necessity of automobiles have directly increased new tyres productions. Nonetheless, all new or used tyres will soon reach their shelf life, termed as end-of-life tyres (ELT) which explain their shocking annual disposal rate of 1.5 billion worldwide. Conventional remedies applied have proven to be less effective given their failure in harnessing the material and energy completely from the ELT. Pyrolysis or thermolysis on the other hand is capable of converting the ELT into useful high value products which are competent as green fuels alternatives to the depleting natural fossil fuels. That said, machineries and technologies capable of pyrolysing the ELT to energy are highly sought after today.

Over the past decades, ELT pyrolysis technologies came in all shapes and sizes but among all, screw or auger reactor is favorable for its simplicity and convincing technology in pyrolysis fuel (oil and solid char) production. The traditional screw reactor comprises an externally heated cylindrical “tube” together with a low-temperature screw shaft responsible in mixing and transporting the feedstocks. The high temperature difference between the heated reactor wall and the cold internal screw shaft has attributed to its lackluster heat transfer performance and risked providing consistent throughput. To overcome the matter, it was suggested that heat should be introduced into the hollow internal screw shaft by means of electric, heated air or fluids or other heating mediums.

Nevertheless, there was limited research on the heat transfer performance across an IHSPR. Meanwhile, a pilot-scaled IHSPR was developed by local renewable energy industry which serves as the research subject in this particular paper.
2. Literature review

2.1. End-of-Life Tyres: Threat and Opportunity

Constructed to withstand severe conditions and having lifespan between 80 and 100 years [1][2], the annual disposal of 1.5 billion [3][4] non-biodegradable, durable and chemically-resilient end-of-life tyres (ELT) globally could bring about devastating effect to the environment. Its mismanagement such as illegal dumpsites pose threats to potential health and environmental hazard, besides the possibility of fire outbreak with high emissions of toxic gases [5][6] and as a breeding ground for disease carrying vectors such as mosquitoes [5][7].

2.2. ELT Pyrolysis

Being an irreversible process simultaneously involving the change of physical phase and chemical composition of the ELT [5], pyrolysis process involved applying significant heat (at temperature 200°C-1200°C) [8][9] on the ELT in an unreactive environment, thereby thermal degrading the ELT to produce high energy density oil, gas and solid char. A typical ELT pyrolysis process generates hydrocarbon gases (5-20 wt%), solid char (30-40 wt%) and oil (40-60 wt%) [9][10] with commendable calorific values of 30-40 MJ/m³, 30 MJ/kg and 41–44 MJ/kg, respectively [5][11][12][13]. The products, however, are low-grade and require further refinement prior to reuse [14].

2.3. Screw/ Auger Reactor

Given its relatively simple construction and familiar operation, the technologies of screw conveyors have long been used intensively and extensively in industries to transport and treat solids materials regularly [15][16]. Screw reactor was first applied in biomass pyrolysis field in year 1969 and was found to be applicable in both fast and slow pyrolysis field [17] with its operation needing little or no carrier gas [16]. Generally, the screw reactor comprised of a tubular externally heated wall with a screw within the reactor conveys and stirs the feedstocks homogenously and repeatedly to improve heat transfer between the feedstocks and the heated wall. The used of motorized screw prevents coagulation of the feedstocks and at the same time allows drive speed alteration which regulates the solid residence time of the feedstocks within the reactor [18] thereby mechanically expelling the resulting char to its reservoir for subsequent feedstocks feeding and thermal degradation process to take place [19]. Lastly, the screw reactor is favorable for its convincing technology in pyrolysis oil and solid char productions [20] and has attracted much interest of many industries.

2.4. Governing Parameters

The governing parameters affecting the tyre pyrolysis system would cover the reactor temperature, particle size of feedstock, and feed rate.

2.4.1. Reactor Temperature. The reactor temperature has been known as one of the most influential parameters affecting the performance of any thermochemical process reactor in its products productions. Countless studies have been carried out and it was found that reactor temperature was manipulated mainly to yield desired outputs, with low temperature favouring solid char production and high temperature favouring pyrolysis gas production.

2.4.2. Particle Size of Feedstocks. Islam [21] has discovered that the increase of feedstocks size resulted in an increase in yield of pyrolysis oil up to a certain extent before the yield started to decrease. It was deduced that larger feedstocks have smaller reaction surface and therefore experienced significantly lower heating rate compared to smaller particles which could be completely thermal-degraded under similar pyrolysis environment.

2.4.3. Feed Rate. Increment of feedstock feed rate lead to proportional increment in volatile matter released during the pyrolysis process. This subsequently reduces the volume available in the reactor...
which reduces the gas residence time and prevented the cracking of gas fractions into permanent gas and consequently yields higher production of liquid oil [11].

2.5. Heat Transfer Theory and Analysis Approach

The newly developed IHSPR was a concentric cylinder with three layers. The interior layer was mainly filled with heated air supplied at a fixed rate from the BFBC. Meanwhile, the exterior layer comprised of recycled heated air aimed to reuse the heated air supplied to maintain the overall temperature of the reactor before it was released into the atmosphere via the exhaust duct. Isolated from the aforementioned layers, the middle layer was where the ELT chips pyrolysis has taken place. It was however only filled with stagnant air at ambient temperature and pressure during ZLHT.

The reactor operated by applying the fundamentals of thermodynamics and heat transfer. Second law of thermodynamics has stated that heat always transfers from high temperature to low temperature. 875 °C of heated air was constantly supplied into the hollow screw shaft (interior layer) while other layers were kept at considerably lower temperature. Meanwhile, the insignificant thickness of the walls separating the vast temperature difference of fluids too has contributed to the relatively large temperature gradient in the radial direction, making it a one-dimensional heat transfer towards the exterior [22]. Concurrently, the considerably constant fluid temperature at their respective layer allows heat transfer through the walls steadily.

On the other hand, the presence of the rotating screw and the concentric cylindrical design of the IHSPR have exacerbated the measurement of pyrolysis temperature. Therefore instead of the pyrolysis region, two k-type thermocouples were installed at the exterior layer of the screw reactor (T_{exterior, inlet} and T_{exterior, outlet}) which were only capable of measuring the temperature of the recycled heated air surrounding the pyrolysis region. The thermocouples were aimed to determine the temperature profile across the pyrolysis reactor and also to indicate the time required to achieve pyrolysis temperature (T_{pyrolysis}), which marked the beginning of ELT chips pyrolysis process.

3. Objectives

- To study the heat transfer performance of the pyrolysis reactor via steady-state heat transfer analysis (SSHTA).
- To evaluate the heat transfer performance of the pyrolysis reactor through products characteristics analysis.

4. Research methodology

Zero-load heating tests (ZLHT) were first conducted on the empty screw reactor to determine the operational parameters and temperature distribution across the reactor. It shall meanwhile indicate the time required for the reactor to achieve pyrolysis temperature, T_{pyrolysis}, which marked the beginning of ELT chips pyrolysis process. With the help of k-type thermocouples and Graphite midi LOGGER GL840 data logger, the temperature throughout the pyrolysis reactor was recorded. The test was carried out thrice. At the same time, the test shall provide the necessary information on the boundary conditions of the heated air supplied into the pyrolysis reactor in steady-state heat transfer analysis (SSHTA). The facilities involved were as shown in Figure 1.

The one-dimensional SSHTA was carried out on the SolidWorks model of the INSPR using SolidWorks Flow Simulation 2016 to study and illustrate the temperature profile across the newly developed reactor. Figure 2 and 3 showed the presence of two separated fluid regions present in the IHSPR design. Figure 4 showed the boundary conditions prepared for SSHTA. The SSHTA would provide adequate information on the temperature gradients especially that of the pyrolysis region. The boundary conditions of the heated air namely, temperature, pressure and flow rate to name a few were determined from the ZLHT carried out earlier.

Lastly, experiments involving ELT chips feed rate manipulations were carried out. Non-specific ELT chips mixture of 100 ± 15 square millimeters without both the steel thread and the textile netting were fed into the pyrolysis reactor with the feed rate ranging from 0.3 kg/min to 0.5 kg/min for duration of two hours. The reactor was not purged with any inert gases as research showed it is rather
redundant and hence less economically viable [11][23] The pyrolysis char and pyrolysis oil produced were collected from their respective reservoir, weighed and sent for characteristics analysis.

Figure 1. IHSPR system.

Figure 2. ELT Pyrolysis region in the IHSPR SolidWorks model.

Figure 3. Heated air region in the IHSPR SolidWorks model.

Figure 4. IHSPR SolidWorks model with the boundary conditions data obtained from ZLHT.
5. Results and discussions

5.1. Zero-Load Heating Tests (ZLHT)
Aside from preventing leakages of pyrolysis fuel and hence ensuring the safety of its operations through the isolation of the pyrolysis vapour from the heated air, the presence of the rotating screw and the concentric cylindrical design concept of the internally heated screw reactor have exacerbated the measurement of pyrolysis temperature. Therefore, instead of the pyrolysis region, there were two k-type thermocouples installed at the exterior layer of the screw reactor (T_{ext, inlet} and T_{ext, outlet}) only capable of measuring the temperature of the heated air surrounding the pyrolysis region. Nevertheless, their contributions were proven vital in evaluating the temperature of the inlet and outlet region of the pyrolysis reactor. After three repetitive ZLHT, it was found that the heated air was supplied at a constant temperature of 875°C at a flow rate of 0.1169 m$^3$/s into the hollow internal screw shaft of the pyrolysis reactor. After two hours of continuous supply, the heated air at the exterior layer of the pyrolysis reactor has achieved 200°C which indicated the interior pyrolysis region of the reactor has definitely achieved pyrolysis temperature [8][9] as shown in Figure 5 below.

![Temperature gradients at both inlets of the developed IHSPR.](image)

**Figure 5.** Temperature gradients at both inlets of the developed IHSPR.

5.2. Steady-State Heat Transfer Analysis (SSHTA)

5.2.1. Mesh Setup. The global mesh comprised of level four initial mesh with first degree of refinement level while the local mesh of cuboid shape were of level three refining cells for fluid and solid cells and fluid-solid boundary, with first degree of refinement level. Figure 6 showed the result of mesh setup on the SolidWorks model of the IHSPR before SSHTA was carried out. There were a total of 1121737 cells. The mesh has generally focused on the body of the IHSPR to gain valuable information on the heat transfer and temperature gradient throughout the pyrolysis and heated air regions.
5.2.2. Flow Simulations. Figure 7 showed the temperature gradients across the developed pilot-scaled IHSPR after it was heated for two hours with a constant heated air input of 875°C and flow rate of 0.1169m$^3$/s. The inlet of the exterior layer of the IHSPR, $T_{\text{exterior, inlet}}$ as indicated has achieved 474.65K which is equivalent to 201.45°C and meanwhile the screw blade or “flighting” has achieved 912.91K which is equivalent to 639.76°C. The convincing temperature results marked the beginning of ELT chips feed rate manipulations experiments which aimed to evaluate the heat transfer performance of the developed pilot-scaled IHSPR through products characteristics.

Figure 6. Mesh setup on the IHSPR SolidWorks model. Red, green and blue colours indicated refinery levels 3, 2 and 1 respectively.

Figure 7. Temperature gradient across the IHSPR SolidWorks model.
5.3. ELT Chips Pyrolysis with Feed Rate Manipulations

For feed rate 0.3 kg/min, the average weight of the products produced were 51.99 % wt char, 25.09 % wt oil and 22.91 % wt gas. In the 0.4 kg/min feed rate experiments, the amount of oil produced was found to increase by 56.2% to 39.19 %wt, with char and gas dropped by 13.46% and 31%, to 15.82%wt and 44.99 %wt, respectively. The trend remain the same in the 0.5 kg/min feed rate experiments, with products char and gas plummeted to 36.18 %wt and 12.06 %wt respectively with the product oil raised to 51.76 %wt. The results clearly indicated increment of feedstock feed rate lead to proportional increment in volatile matter released during the pyrolysis process. Subsequently the volume available in the reactor reduces which reduces the gas residence time and prevented the cracking of gas fractions into permanent gas and consequently yields higher production of liquid oil.

Figure 8. Products distribution at 0.3 kg/min ELT chips feed rate.

Figure 9. Products distribution at 0.4 kg/min ELT chips feed rate.

Figure 10. Products distribution at 0.5 kg/min ELT chips feed rate.

Figure 11. Mean products distribution for manipulated ELT chips feed rate.

5.4. Proximate Analysis Using Thermogravimetric Analyser

To determine the compositions namely moisture, volatiles, fixed carbon and ash present in the products, proximate analysis via Thermogravimetric Analyser (TGA) was conducted in Center of Excellence for Advanced Research in Fluid Flow (CARIFF) Universiti Malaysia Pahang. The temperature range was set to be from 30°C to 900°C with the heating rate set to 50°C/ min and air flow rate of 20ml/min was set. The vast temperature range was set to determine the overall decomposition gradient of the products. High heating rate was set to speed up the thermal degradation process since the detail decompositions of impurities and mineral matter were not required. Knowing that the carbon black would most probably remain unchanged because of its inertness under nitrogen atmosphere [24] and meanwhile to determine the percentages of ash within the products, air was used instead of nitrogen gas [25]. Nonetheless, the results obtained from the TGA analysis were rather
astonishing given the decomposition curves not only did not illustrate the compositions present within
the products at all, they were no significant difference among products of different feed rate. It was
hypothesized that the ELT chips were pyrolysed in an oxygen-rich environment, thereby altering the
thermochemical decomposition of the ELT chips from that of the conventional pyrolysis process. The
decomposition curves for the products were as shown from Figure 12 to 17.

**Figure 12.** TGA analysis of 0.3 kg/min pyrolysis char.  **Figure 15.** TGA analysis of 0.3 kg/min pyrolysis oil.

**Figure 13.** TGA analysis of 0.4 kg/min pyrolysis char.  **Figure 16.** TGA analysis of 0.4 kg/min pyrolysis oil.

**Figure 14.** TGA analysis of 0.5 kg/min pyrolysis char.  **Figure 17.** TGA analysis of 0.5 kg/min pyrolysis oil.

6. Conclusion
Heat transfer performance study was carried out on a pilot-scaled IHSPR developed by local
toxic energy industry. With the operational parameters obtained from ZLHT, SSHTA results
showed convincing temperature gradient across the reactor after it was heated for two hours, which
marked the beginning of ELT chips feed rate manipulations experiments. There were noticeable
reductions in the productions of pyrolysis gas and char but otherwise for pyrolysis oil as the feed rate
increased from 0.3 kg/min to 0.5 kg/min. However, the compositions namely moisture, volatiles, fixed
carbon and ash within the pyrolysis oil and char remained unknown as they were undetectable through
the set TGA environment. Future experiments shall be conducted in a nitrogen-purged environment to challenge and verify the findings discovered by Agirre, Griessacher, Rösler and Antrekowitsch [23] and Alkhatib [11].

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