Cost-Effective Design of Exhaust Waste Heat Recovery System: A Numerical and Optimization Approach

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Abstract- **This research paper introduces a novel cost-effective design for a Diesel Exhaust Waste Heat Recovery System (WHRS) tailored for both Bus Rapid Transport System (BRTS) in Jaipur and stationary applications. The proposed design aims to fulfill the essential design constraints for WHRS while ensuring robustness and adherence to Indian Pollution Control Standards. The study employs numerical simulations and optimization techniques using CFD software, specifically Ansys FLUENT and Ansys Workbench, with a parametric study approach. The optimization process considers various waste heat recovery system geometries, ensuring compliance with both performance requirements and geometrical constraints. The presented design offers a promising solution for efficiently harnessing waste heat in diesel exhaust, contributing to sustainable and energy-efficient transportation and stationary systems.**

Keywords– Computational Fluid Dynamics (CFD), Waste heat recovery system (WHRS), Ansys

1. INTRODUCTION

Securing future prosperity necessitates the prudent management of limited resources, encompassing heightened demand, scarcity, and the environmental repercussions of energy consumption. Computational Fluid Dynamics (CFD) employs computer-based simulations to investigate complex systems, delving into aspects such as fluid dynamics, heat transfer, and various phenomena, including chemical reactions [1].

The examination of systems encompassing fluid dynamics, heat transfer, and diverse phenomena, including chemical reactions, relies on computer-based simulations known as CFD [2-3]. This high-throughput system executes millions of calculations to simulate the interactions of liquids and gases with engineering processes [4]. How to deal with the continuous liquid in the separation of the computer is the most important thing in CFD. One method of solving equations of motion is to determine the spacing in small cells to form a grid or mesh (Euler's equations for in viscous flow and Navier Stokes equations for viscous flow). Many researchers [5-7] reported the modelling of the shell and tube heat exchanger analysis with the help of CFD tool. Jasdeep et al. [8] and Roy et al. [9] presented the analysis of novel waste heat recovery system utilizing the heat coming from exhaust of internal combustion engines. Additionally, such meshes may be irregular (such as 2-dimensional triangular entities or 3-dimensional pyramidal entities) or regular; The difference from the original is that each cell must be stored in the individual's memory.

When the network can be solved in all dimensions, the Navier Stokes equations for laminar and turbulent flow can be solved directly (direct numerical simulation). However, typically, the scale required for addressing the problem exceeds the capabilities of today's supercomputers. In such scenarios, turbulence simulations must accurately depict complex turbulence patterns. Two prominent methods employed to handle this scale are Large Eddy Simulation and Reynolds-Averaged Navier-Stokes formulations, often utilizing the k-ε model or Reynolds Stress Model. Additionally, alongside the Navier-Stokes equation, other equations are frequently solved concurrently.

Zahid Anwar et al. [10] worked on experimental research on heat recovery in R744-based refrigerants. The Applied Thermodynamics and Refrigeration Division has developed a new CO2 cooling/heat pump test rig for the examination of CO2 cooling/heat pump systems. In the publication of this study, the following key tasks were performed using newly developed equipment:

- Overall performance in the different processes used.
- Evaluation of compressors and different heat exchangers as simple devices.

Rathore and Bargely [11] analyzed the heat transfer using a finned tube and bared tube type shell and tube heat exchanger with the help of CFD tools. The analysis shows that there is a vast exploration of the results could be possible with the help of CFD detailing effect on various output parameters such as pressure, velocity and temperature variations. Catapano et al. [12] analyzed the Stirling cycle running on a waste heat recovery system from an internal combustion engine. It was concluded that the geometrical design is a dominating factor in the design of a WHRS. Tian et al. [13] reported challenges and issues with waste heat recovery systems based on internal combustion engines and concluded that system design is quite dominating in the efficient output of the study. Gohar et al. [14] reported recovery and effective utilization of internal combustion engine-based waste heat recovery system.

The primary objective of this study is to initiate a CFD investigation on a novel heat exchanger variant known as Waste Heat Recovery System (WHRS). The aim is to assess the impact of temperature elevation and pressure variation on two distinct designs of heat exchangers. In this analysis, the exhaust gases from a diesel engine serve as the external fluid within a rectangular shell for heat transfer evaluation, while air functions as the internal cold fluid within tubes, including rectangular and circular types.

2. MATERIALS AND METHOD

The recuperation of heat from the exhaust gases of internal combustion engines has become imperative considering diminishing conventional energy resources and the escalating costs associated with them over the years. The pressing need to utilize energy more efficiently has arisen due to the substantial surge in fuel prices. The continuous upward trajectory has compelled researchers and engineers to actively seek ways to curtail the release of waste heat into the environment from internal combustion engines.

Gas emissions from different places and different temperatures are often discharged into the local environment and this is used for some important purposes in the community. The best way to recover heat is with a heat exchanger. Many types of HE is available for this purpose, but the costs of developing any system in developing countries are significant. Therefore, there are currently no encouraging signs of e-waste use in India.

This study conducted a numerical analysis aimed at recovering heat from internal combustion (I.C.) engine exhaust gas. Various designs were investigated to identify the most efficient Waste Heat Recovery System (WHRS), with selection criteria focused solely on thermal efficiency and the temperature difference achieved. Additionally, a parametric analysis was performed to understand how altering flow parameters affects the system.

The method measures all thermal effects of internal and external switching valves and fouling factors. Generally, thermal designers can determine this themselves with reasonable accuracy and with little difficulty. According to the results of the analysis, the finned tube heat exchanger is more expensive than the tube heat exchanger due to the higher fluidity and pressure drop along the tube, which prevents the tube from getting dirty. Conventional heat exchangers have a slightly lower pressure drop on the shell side. Prevents contamination and fluid transfer while protecting the pipe from the outside.

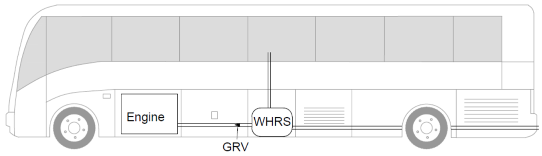

Fig 1. *Schematic of the experimental setup*

The primary concern revolves around the compact geometry of the Heat Exchanger (H.E.), making it easily deployable in any trunk or fixed room connected to the Internal Combustion (I.C.) engine. However, this characteristic may render the H.E. unsuitable for its intended purpose. Multiple simulations were run to assess the design quality of the Waste Heat Recovery System (WHRS).

While both designs appear viable for production, circular fins exhibit greater strength compared to rectangular tubes. All dimensions and parameters are illustrated in Fig. 2 and Fig. 3. The study assumes that the waste heat recovery system is constructed from aluminum materials, featuring an insulating layer appropriately positioned within the system's body.

Considering a pipe thickness of 3 mm and a wall panel thickness of approximately 30 mm, including the exterior insulation, the WHRS weighs about 100 Kg, a reasonable weight for the Bus Rapid Transit System (BRTS). Addressing a significant back pressure issue in the heating back, a valve is installed to mitigate the problem. The current research predominantly focuses on CFD simulations, assuming valve integration during the production phase.

The configurations have been reported in Table 1. These are the helpful parameters while simulating the waste heat recovery system in CFD environment. Furthermore, this analysis analyzes the velocity, temperature, energy and Prandtl number contours which are already reported in the published article by authors [15]. As per the provided configuration analysis is done which is then shown in the subsequent sections of the

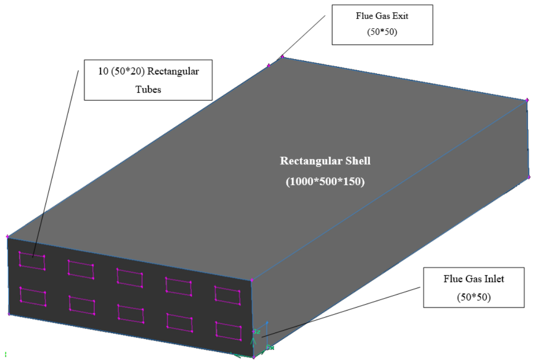

***Fig 2** Design 1 Rectangular Tubes*

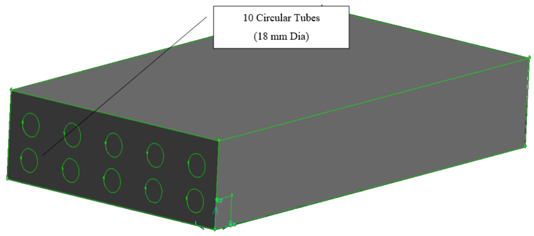

***Fig 3** Design 2 Circular Tubes*

Table 1: Configurations of parameters for CFD simulation of WHRS

Case. No		Shell Configuration		Tube Configuration	
		Velocity (m/s)	**Temp. (K)**	**Velocity (m/s)**	**Temp. (K)**
1		1	450	0	300
2		1	450	0.5	300
3		1	450	1.0	300
4		1	450	1.5	300
5		1	450	2.0	300

3. RESULT AND DISCUSSION

In addition to pipes, this addition can reduce the cost of headers, shells, baffles, and pipe plates (smaller diameter, smaller wall thickness, fewer pipe holes, less alloy lining material, etc.).

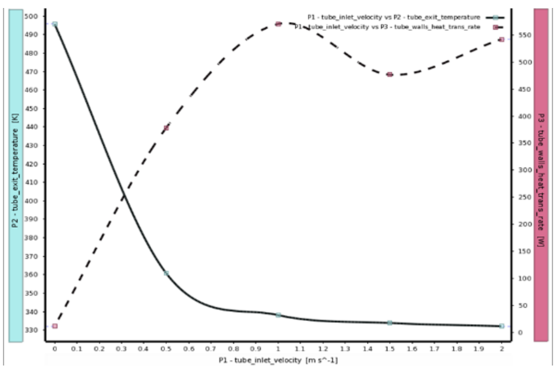

***Fig 4.** Parametric study of WHRS (Rectangular tubes) at V_{shell}=1m/s*

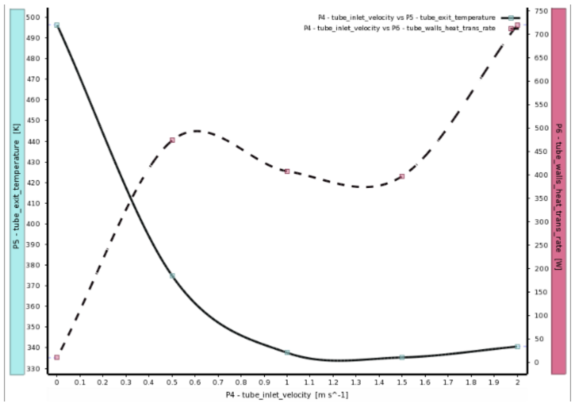

***Fig. 5** Parametric study of WHRS (Circular tubes) at V_{shell}=1.5m/s*

The purpose of this analyzes the various different turbulence models in CFD tools use standard model, RNG model, Realized model and RSM model with high-speed wiring diagram for simulation. Increases in computational power have allowed models to respond to polyphase flows with high resolution in realistic geometries.

As shown in Fig 4, the rectangular tube have been regularly observing drop in temperature which is obvious but heat transfer rate is evidently high during the velocity range of 0.5 to 1.0 m/s. Similar characteristics of temperature profile and heat transfer has been observed in the case of round tubes. However, a small drop in the heat transfer rate is observed as compared to the earlier case when velocity increases.

The evident outcome is depicted illustrating the total power of the Waste Heat Recovery Systems (WHRS) for both designs. The observation leads to the conclusion that the two systems exhibit a comparable thermal impact on the profile image. The disparity lies in the total power of the tube, which varies between the two waste generators.

As an outcome of the study both the configurations show better results in the range of 0.5 to 1.0 m/s velocity, but round tube has been preferred over rectangular tube due to ease in manufacturability.

4. CONCLUSIONS

In conclusion, the experimental investigation and numerical simulation in the present research focused on the cylindrical and rectangular shell side of a heat exchanger. Employing commercial fluency software allowed for the comprehensive simulation of the flow field and heat transfer performances within the shell side. This approach provided valuable insights into the properties of heat transfer, contributing to a deeper understanding of the thermal behavior in the specified heat exchanger configuration.

In the present study, a waste heat recovery system has been modelled using Fluent Gambit software to analyze the effect of velocity of exhaust gas flow and temperature. Here, two configurations with rectangular and circular tubes with 5 combinations of velocities and temperatures have been studied and analyzed. As reported from the results, both designs work well, but as a returnable power supply the round tube is easier to manufacture. Furthermore, parametric study shows that the water velocity in the tube is most effective in the range of 0.5 m/s to 1.0 m/s for both WHRS designs. There are some minor changes to the engine's system to incorporate the outcome of the study.

The proposed design presents a promising avenue for addressing the pressing issues of escalating energy demand, dwindling resources, and environmental apprehensions. Through thorough analysis of outcomes and elucidation of pivotal findings, this study lays the groundwork for forthcoming breakthroughs in the domain of exhaust waste heat recovery systems. By forging ahead, it promises to usher in a new era characterized by cost-effective, high-efficiency, and eco-conscious solutions, thus aligning with the overarching aspiration of fostering sustainable and energy-efficient frameworks for the collective betterment of society.

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