AMMONIA BASED EXHAUST HEAT RECOVERY SYSTEM FOR HYBRID VEHICLES

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Abstract

Conventional automobiles employ Internal Combustion engines (IC engines), which emit a large quantity of heat. Combustion heat radiates a significant amount of heat into the atmosphere; nevertheless, this wasted heat can be used in our heat recovery system, that transforms waste heat into useful energy. The utilization of thermal energy that would otherwise be lost to the environment to perform a useful activity is known as waste heat recovery. A hybrid vehicle has both an internal combustion engine and an electric powertrain either connected in series or parallel. This heat recovery system can be used in a hybrid vehicle to recover useable energy in the form of electrical energy for later use. The heat is dissipated by convection in the powertrain or engine, where it is transferred to the cooling circuit or lost out the exhaust pipe as exhaust gases. The heat recovery unit is a thermochemical recovery system that can be fitted in an engine's cooling system. The engine's coolant heat can be used to turn a working fluid into steam which in turn can be used to power a turbine to produce electricity. Also it can be stored in a battery pack and used for productive work in a hybrid vehicle. As a result of this design, we may obtain greater range and improve the hybrid system's overall effectiveness.

1 Introduction

Current advances in the best ways to put deployable sources of energy to beneficial work in order to minimize fossil fuel usage and pollution. Internal Combustion engines are the world's largest consumers of fossil resources, out of all available sources. About 30 - 40 % of the total heat provided to the engine in the form of fuel is transformed into meaningful mechanical work while the rest are released into the atmosphere via exhaust gases and engine cooling systems, resulting in an increase in entropy and significant pollution, hence it is necessary to convert waste heat into beneficial labour. Recovery and utilisation of waste heat not only saves fuel, but also minimises waste heat and greenhouse gas emissions into the atmosphere. It is critical to make a serious and concerted effort to conserve this energy using exhaust heat recovery technology. The overall energy needs and the impact on global warming would be reduced as a result of waste heat recovery. Utilizing the internal combustion engine as the primary power source alongside with the stringent emission norms and the rising fuel costs, many manufacturers attempt to create a complex engine that could work with improved efficiency to enhance and decrease the fuel consumption.

To enhance the thermal efficiency, engine manufacturers have used techniques including enhanced fuel-air mixing, turbocharging, and variable valve timing. However, 60-70 % of the fuel energy is wasted as waste heat in the coolant or exhaust. Furthermore, as pollution rules become stricter, engine manufacturers are limiting combustion temperatures and pressures, thus reducing the potential operational efficiencies. Engines have consumed more than 60% of fossil oil as the most frequently used source of primary power for machinery crucial to the transportation, construction, and agricultural sectors. Legislation governing exhaust emission levels, on the other hand, has focused on Carbon monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NO_x), and Particulate Matter (PM). Conservation of energy on engines is one of the most effective approaches to address these issues because it improves the engine's energy utilisation effectiveness while also lowering pollutants. Given the necessity of improving energy conversion efficiency for lowering engine fuel consumption and emissions, scientists and engineers have conducted numerous successful studies targeted at improving engine thermal efficiency, such as supercharging, lean mixture combustion, and so on.

A heat recovery system for 16 TR air conditioning unit was designed and fabricated in order to generate hot water for daily purpose [1]. S. Karellasa et al., [2] studied heat recovery from exhaust gases in a cement plant thermodynamically, in order to increase the efficiency of the plant. M. Hatazawa [3] developed a sound wave generator by means of heat recovery from gasoline engine exhaust gases and studied various performance characteristics. D. A. Arias et al., [4] investigated waste heat recovery from a spark ignition engine running on a hybrid vehicle and implemented several Rankine cycle configurations. J. Vazaquez et.

al. [5] reviewed various investigations carried on thermo-electricity generation from exhaust gases produced during combustion in internal combustion engines. N. Hossain, and S. Bari [6] suggested various design parameters for a tube and shell type heat exchanger with ammonia and HFC-134a as working fluid in order to recover waste heat from diesel engine by implementing an organic Rankine cycle. Reduction of fuel consumption for air conditioning purpose by means of heat-generated cooling through waste heat recovery was coined [7]. T. Endo et. al., [8] carried out exergy optimization analysis of waste heat recovered from hybrid vehicles to run a Rankine cycle system for power generation.

Z. Ayub and S. Sami [9] discussed various types of heat exchangers employed for Ocean Thermal Energy Conversion system with ammonia and R-134a as working medium. F. Ji et. al., [10] developed a small-scale heat recovering system using Tesla turbine and investigated various performance characteristics to increase the thermal efficiency. Y. Zhang [11] reviewed various thermoelectric generators in recovering waste heat from automotive exhausts. A thermoelectric cooler refrigeration system was designed by [12] using a thermoelectric waste heat recovery module. Y. Quan et. al,[13] discussed aerodynamics-based design aspects of high temperature 80kW axial type Impulse turbine with siloxane MM as working medium in order to run an organic Rankine cycle. A. Chenduran et. al., [14] designed a low-cost steam turbine driven by renewable energy sources for a small-scale thermal power plant. Development of Parsons's turbine and problems faced during reaction turbine operation are briefly discussed [15].

Matter of fact, with every energy-saving technology investigated, one of the most efficient methods is engine exhaust heat recovery. Many researchers have recognised that waste heat recovery from engine exhaust has the capability to minimize fuel usage while reducing emissions and modern technology improvements had enabled such techniques feasible yet economically efficient.

2 Experimental investigation

The focus of this research is to recover wasted heat energy by boosting the thermal efficiency of the engine in order to extend the range of the vehicle and lower its carbon footprint. This project intends to improve the hybrid system's reliability as well as the cooling circuit and the engine's fuel economy. This experiment designed and built an experimental prototype to validate the concept of a heat recovery system as well as analyses various working fluids, component efficiency, system temperature and pressure and turbine power generation. An internal combustion engine produces a significant amount of heated flue gases. A substantial amount of primary fuel might well be saved if some of this waste heat could be managed to recover. It is determined by the mass flow rate and temperature of the exhaust gas and this waste energy can be converted into usable electrical energy.

Figure 1 depicts the architecture of the system built and the waste heat recovery system is reliant on a working fluid that can vaporise at temperatures below that of water. Since ammonia vaporises at extremely low temperatures, it is an ideal working fluid. When the heat source transfers heat energy to ammonia, it immediately vaporises and the vaporised ammonia is adjusted to fit the working conditions of a turbine that transforms heat energy to mechanical energy which ultimately results in electrical power generation. The ammonia vapour drives a turbine, which spins a generator to generate power. The ammonia vapour must be recirculated as a cycle after rotating the turbine. Only when the ammonia condenses into liquid, which is accomplished via a condenser, is recirculation conceivable. The condensed ammonia is pumped back into the evaporator, which efficiently transfers heat from the engine to the ammonia. With the thermochemical recuperation process, engine exhaust gas that emits a large amount of heat into the atmosphere for no reason is reused to generate electricity.

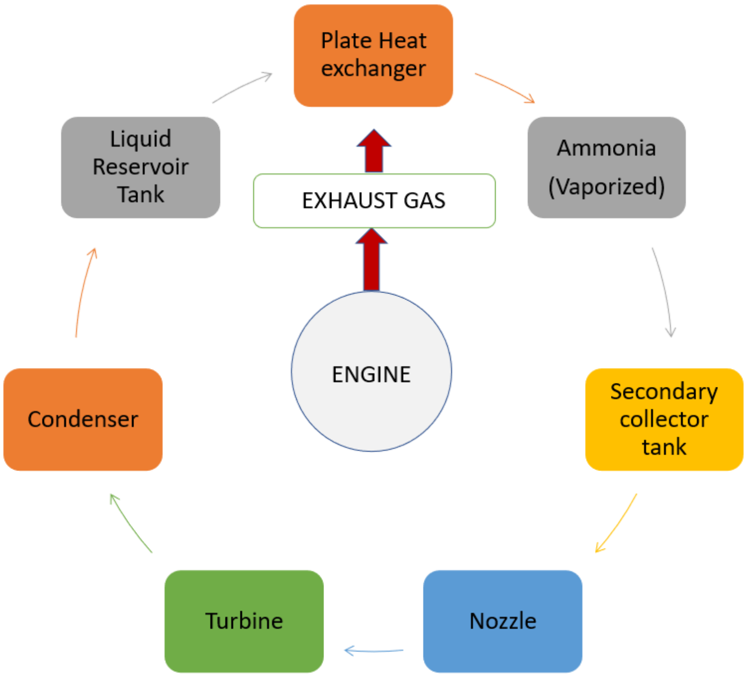

Figure 1. Architecture of the heat recovery system

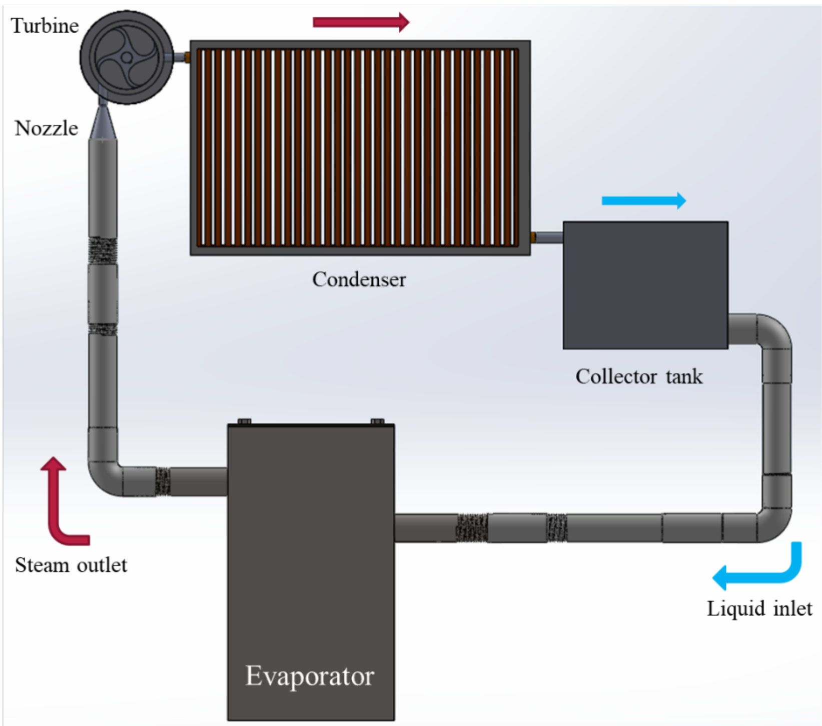

Figure 2. Assembled 3D model of the heat recovery system

The heat radiated from this area of the engine is the most accessible because the exhaust products from a combustion are at extremely high temperatures ranging between 310 and 460℃ depending on the vehicle and also, they converge into a single exhaust. A plate heat exchanger transfers heat from the exhaust to the working fluid and functions as an evaporator, vaporising the ammonia. For the turbine to perform optimally and efficiently, the vaporised ammonia must be pressurised, which is done by a secondary collector tank. To boost the velocity, the pressurised vapour is sent via a nozzle. The turbine, which creates power, is propelled by high-pressure, high-velocity vapour. The vapour must then be condensed and returned to the evaporator, which is accomplished with the help of a condenser. The mass balance for the evaporator is achieved by filling a liquid reservoir tank with condensed liquid ammonia.

The experimental setup must be planned and built with components that meet industrial standards and are not available in modest quantities at retail. To solve this, a small number of components must be designed and built utilising additive manufacturing techniques to expedite the process. Utilizing Solidworks, a 1:1 scaled model of the elements, comprising of piping and fittings, enables for a comprehensive integration of these parts, allowing us to envision the actual arrangement. To aid comprehension, the arrangement is depicted as a process model in Figure 2. Evaporation can be done in a batch or in a continuous mode. The goal of this analysis is on evaporation as a continuous process, with continuous feed and product streams and constant concentrations. The best and most efficient type of evaporator is the plate evaporator; however, it is too difficult to purchase from a store for a functional prototype, thus it is designed and manufactured with ammonia to be filled and must be a mass equilibrium-based design.

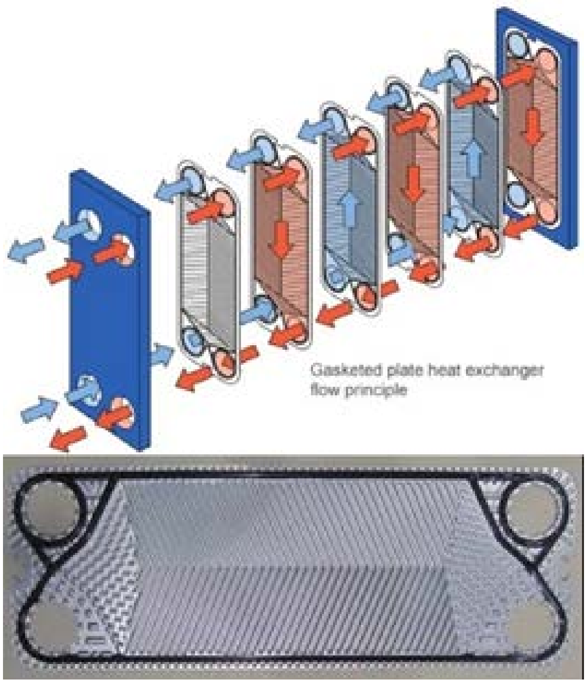

Figure 3. Plate heat exchanger

A receptacle that could fill ammonia to a particular volume with an entrance to fill ammonia and an outlet for the ammonia vapour is developed accordance with the design constraints. The inlet is from the condenser collector tank, and it fills a set volume at the pipe's level. The vapour from the outlet is directed through a nozzle, which enhances the velocity of the vapour and so improves the turbine's performance. Since the container is concerned with capacity, it is constructed with height of 145mm and must be equipped with standard plumbing pipes for later customization. The container should have an aperture for maintenance and access to the heating element, but it should also be able to shut tightly so that the vapour does not escape.

The evaporator is made out of mild steel sheets with a thickness of 1.6mm, which was chosen because it is the minimal thickness for TIG welding. Considering ammonia does not corrode metals, mild steel was used. Split plates with a rubber gasket sandwiched between them provide airtight sealing, which is made intact by bolted joints. A plate heat exchanger as depicted in Figure 3 is made up of a series of parallel plates that are stacked one on top of the other to generate a series of channels through which fluids can flow. The channel in which the fluid flows is formed by the space between two adjacent plates. Hot and cold fluids pass through alternating channels in the exchanger through inlet and outlet holes in the corners of the plates, ensuring that a plate is always in touch with the hot fluid on one side and the cold fluid on the other. The plates' corrugation forces the fluid to follow a winding course, creating a distance between two adjacent plates about 1 to 5 mm.

Semi-welded Plate Heat Exchangers (PHE) are the best option when one of the media is incompatible with the gaskets. Laser welded modules are used to assemble our semi-welded PHEs. For applications such as ammonia condensers, these are quite beneficial. This heat exchanger takes an unusual technique as laser welding is used to join alternate channels. In the welded channels, aggressive media (such as ammonia) flows. Gasketed channels carry non-aggressive media (such as brine or water). Despite its partially welded design, the unit is simple to disassemble for gasket replacement or other maintenance. Figure 4 shows the condenser which is used with the system to condense the steam from the turbine and change its phase to liquid. After being condensed, the liquid ammonia is transferred to a reservoir tank, where it can be recirculated to complete the cycle.

Figure 4. Fabricated condenser

A turbine [16, 17] is a rotational mechanical device with a rotating rotor that harvests energy from a fluid flow and transforms it to work. When paired with a generator, the work performed by a turbine can be used to generate electrical power. The working fluid includes both potential and kinetic energy, which is used to spin the turbine's static air foils. By accelerating the fluid via a nozzle before it reaches the turbine, the fluid's pressure head is transformed to velocity head. The power transmission for impulse turbines is described by Newton's Second Law. We devised and built the slightest in architecture impulse turbine that consists of a row of nozzles preceded by a row of blades, with $V=2\Delta h$ for gas expansion conversion. The absolute velocity increases as the static pressure in the nozzle falls. The blades must rotate at about half the speed of the gas jet to achieve maximum energy transmission. The degree of reactivity in the impulse turbine is zero. The absolute exit velocity must be axial to achieve the highest usage factor. Figure 5 shows a bespoke the fabricated impulse turbine, which has a 12 mm inlet and 12 mm output valve, respectively, with the inlet acting as a nozzle to accelerate the steam jet for a more efficient turbine.

Figure 5. Designed Impulse turbine

The turbine [16, 17] is a four-bladed construction with a unique shape. The turbine's interior construction is a nicely structured parabola that absorbs the impact of the jet stream as kinetic energy and converts it to angular momentum, enabling the turbine to spin. The stationary blades of an impulse turbine turn a portion of the heat in the steam into velocity. As we know, fluid goes from a high-pressure to a low-pressure zone, therefore the input is a high-pressure valve at 28 psi, and the outflow is at air pressure. The turbine diameter is 150 mm with inlet and outlet port diameter of 12 mm and a 32 mm bearing, the shaft is meant to rotate. With an overall working volume of 65.498cm^3 the turbine rotates with the ammonia stream to generate power. The steam tends to migrate towards the low-pressure region after impact, hence the outlet valve is angled to allow for a complete flush of the existing steam. The cycle continues to rotate the turbine and create power from the turbine's shaft-connected generator which produces 12V DC at its rated speed.

For the prototype design, we have made use of ammonia in diluted form mixed with water in a proportion of 36% also known as ammonia water or ammonia solution. Various concentration levels of ammonia have been tested assuming the exhaust temperature at 100℃ for enabling easy calculations is as elucidated in Table 1 and finally 36% proportion is chosen based on the thermal parameters.

Table 1. Behaviour of Ammonia at various concentrations

Temperature of exhaust	Ammonia %	Boiling point (°C)	Energy req for converting ammonia to vapour (KJ)	Additional heat req to convert ammonia to vapour (°C)
100℃	100%	-33.35℃	-63.35KJ	Not required
100℃	75%	27.7℃	52.6KJ	Not required
100℃	36%	96.3℃	183KJ	35-40℃

3 Results and discussion

Instead of displaying the full engine, which would add time and complexity to the fabrication, employing a heating coil to stimulate the heat of an engine saves time and effort. The heating coil must evaporate the ammonia inside the evaporator and raise the vapor's velocity in order for the turbine to revolve and produce power. The vapour from the turbine must be condensed, which is accomplished by a condenser unit, and then transferred to a reservoir tank, where it is used for the evaporator's mass balance. The evaporator is developed and built with the aforementioned factors in mind which is as shown in Figure 6. The fabricated evaporator is then meticulously assembled to ensure that everything is as perfect as possible. There is an aperture for future ammonia operations and the fitted heating element. The heating coil is sealed and fastened to the seal plate by attaching the seal plate to the heating coil with a rubber gasket in between, ensuring that no ammonia vapour leaks even if the seal plate is pressurised. To connect the other components of the arrangement, conventional 20mm GI pipes are used. The heating element is electrically grounded to the evaporator body to avoid electrical leaks. The heating coil produces a max heat of 140℃ and the actual heat obtained throughout the experiment was 133.3℃.

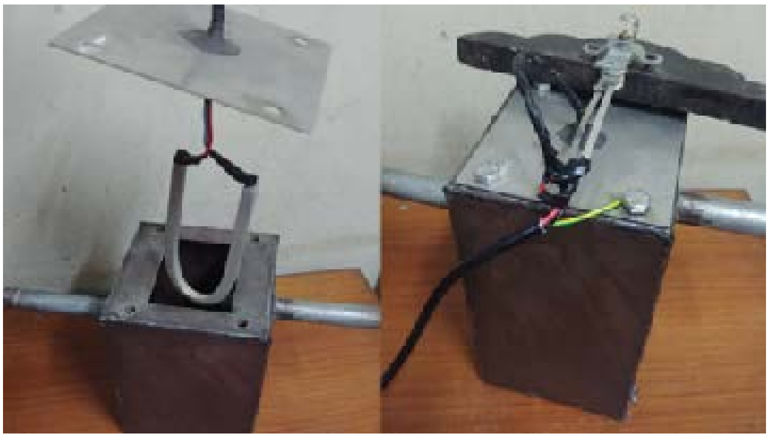

Figure 6. Assembled prototype heating system for evaporator setup

The parameters for framing the formulations and getting the efficiency of the turbine is as follows,
Inlet pressure, $P_1 = 1.5\ Bar$
Inlet temperature, $T_1 = 133.3℃$
$h_1 = 1785.423\ KJ/Kg$
$S_1 = 7.1927 \frac{KJ}{Kg-K}$
Outlet pressure, $P_2 = 0.5\ Bar$
$hf_2 = -22.3\ KJ/Kg$
$hg_2 = 1381.6\ KJ/Kg$
$sf_2 = -0.096 \frac{KJ}{Kg-K}$
$sg_2 = 6.057 \frac{KJ}{Kg-K}$
$S_1 = S_2 = sf_2 + X_2(sg_2 - sf_2)$ [18] (1)
Dryness fraction, $X_2 = 1.184$
$h_2 = hf_2 + X_2(hg_2 - hf_2)$ [18] (2)
$h_2 = 1639.917\ KJ/Kg$
Absolute velocity at inlet, $V_{a1} = 44.72\sqrt{h_1 - h_2}$ [18] (3)
Upon substituting the value of h_2 from Equation (2) into Equation (3) we get, $V_{a1} = 539.412\ \frac{m}{s}$
The blade velocity, $u = 150\ m/s$
The nozzle inclination to wheel, $\alpha_1 = 20°$

The velocity triangle for the chosen turbine with the parameters is shown below in the Figure 7.
Whirl velocity, $V_{w1} = V_{a1}\, cos\, cos\, \alpha_1$ [18] (4)
Upon substituting the value of V_{a1} from Equation (3) into Equation (4) we get, $V_{w1} = 506.881\ m/s$
Axial inlet of absolute velocity at inlet, $V_{f1} = V_{a1}\, sin\, sin\, \alpha_1$ [18] (5)
Upon substituting the value of V_{a1} from Equation (3) into Equation (5) we get, $V_{f1} = 184.489\ m/s$
Blade angle at inlet, $\beta_1 = \left(\frac{V_{f1}}{V_{w1}-u}\right)$ [18] (6)
Upon substituting the value of $V_{w1}\ and\ V_{f1}$ from Equations (4) and (5) into Equation (6) we get, $\beta_1 = 27.33°$
Relative velocity at inlet, $V_{r1} = V_{a1}\, sin\, sin\, \beta_1$ [18] (7)
Upon substituting the values of V_{a1} and β_1 from Equations (3) and (6) into Equation (7) we get, $V_{r1} = 247.652\ m/s$

Neglecting the frictional losses, the blade velocity coefficient, $k = \frac{V_{r2}}{V_{r1}} = 0.8$
Now $V_{r2} = k * V_{r1}$ (8)
Upon substituting the value of V_{r1} from Equation (7) into Equation (8) we get, $V_{r2} = 222.886\ m/s$

The outlet velocity diagram is as shown in Figure 8 and the outlet blade angle, $\beta_2 = 30°$

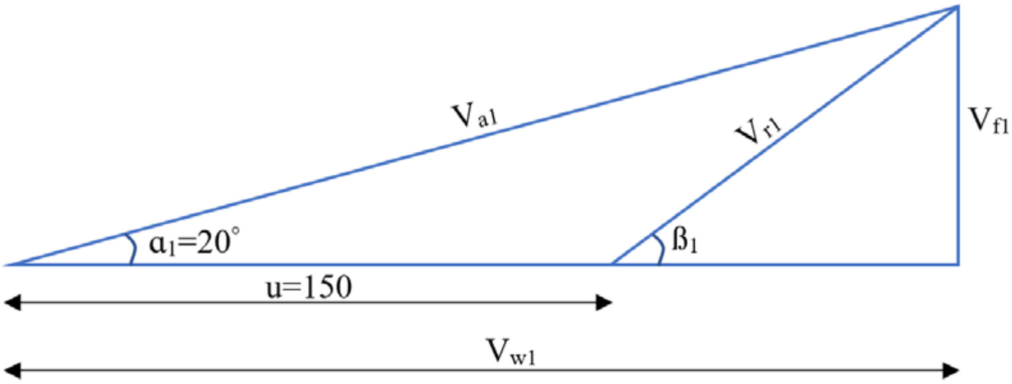

Figure 7. Velocity triangle of impulse turbine

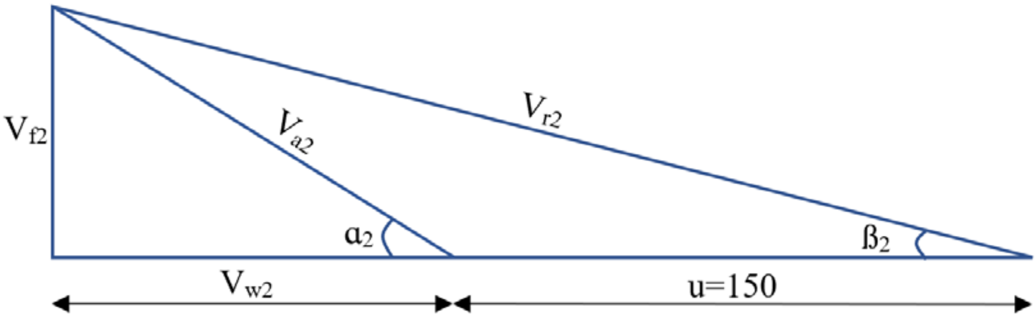

Figure 8. Velocity diagram of outlet side

$cos\ cos\ \beta_2 = \frac{V_{w2}+u}{V_{r2}}$ [18] (9)

Now, $V_{w2} = (V_{r2} * cos\ cos\ \beta_2) - u$ (10)

Substituting the values from Equation (8) into Equation (10) we get, $V_{w2} = 43.025\ m/s$

$V_{f2} = V_{r2} * sin\ sin\ \beta_2$ [18] (11)

Substituting the values of V_{r2} from Equation (8) into Equation (11) we get, $V_{f2} = 111.443\ m/s$

The power developed in the turbine is, $P = \dot{m}(V_{w1} + V_{w2})u$ [18] (12)

The tangential force $F_t = \dot{m}(V_{w1} + V_{w2})$ [18] (13)

$\dot{m} = 10Kg/min$

$F_t = \frac{10}{60}(506.881 + 43.025)$

$F_t = 91.651N$

Speed ratio, $\rho = \frac{u}{V_{a1}}$ (14)

$\rho = 0.278$

Power developed, $P = F_t * u$ (15)

Substituting the values from Equation (13) into Equation (15) we get, $P = 13.7\ KW$

The blade efficiency, $\eta_B = \frac{(V_{w1}+V_{w2})*u}{\frac{1}{2}V_{a1}^2}$ [18] (16)

Substituting the values of $V_{a1}, V_{w1}\ and\ V_{w2}$ from Equations (3), (4) and (10) into Equation (16) we get, $\eta_B = 56.7\%$

Axial thrust, $F_y = m * (V_{f1} - V_{f2})$ [18] (17)

Upon substituting the values of $V_{f1}\ and\ V_{f2}$ from Equations (5) and (11) we get, $F_y = 12.174N$

Angular velocity, $\omega = \frac{u}{r}$ [18] (18)

$\omega = 2000\ rad/s$ since the radius of the turbine is set at 75mm

Speed of the turbine, $N = \frac{\omega * 60}{2 * \pi}$ [18] (19)

Upon substituting the ω value from Equation (18) into Equation (19) we get, $N = 19098\ RPM$

Torque generated in the turbine, $T = \frac{P}{\omega}$ [18] (20)

Upon substituting the values of $P\ and\ \omega$ from Equations (15) and (18) into Equation (20) we get, $T = 6.85\ Nm$

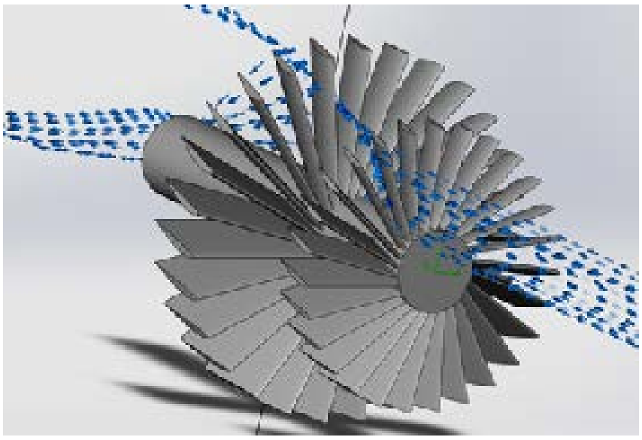

Figure 9. 3D model of the fabricated reaction turbine

The theoretical efficiency as calculated from the Equation (16) for the used heating element is found to be 56.7% at the turbine speed of 19098 RPM from Equation (19) with maximum torque of 6.85Nm arrived from Equation (20). For carrying out the trial in an effective manner the heating element is provided with a current regulator with which the heating temperature can be varied to offer a range of temperatures to obtain the results which could further lead to an inference. A 3000 RPM 12V alternator is coupled to the turbine via a spur gear reduction unit in a gear ratio of 1:6.4 with which more torque is offered for the generator to produce current. The second stage of the experiment consists of altering the turbine with an axial reaction turbine whose rotational torque generated is obtained below with stage 1 consisting of 22 blades and stage 2 consisting of 34 blades as depicted in the Figure 9.

4 Conclusion

The research presented in this paper introduces a novel ammonia-based exhaust heat recovery system tailored for hybrid vehicles, addressing the critical need for enhancing energy efficiency while minimizing environmental impact. The system exploits the unique thermophysical properties of ammonia, such as its low boiling point, to recover waste heat from engine exhaust. This heat is effectively utilized to generate electrical energy through a turbine, which can be stored and used to augment the hybrid powertrain's performance. A functional prototype was successfully developed and tested, demonstrating the viability of the proposed system. The results indicate significant potential for improving engine thermal efficiency, reducing fuel consumption, and lowering greenhouse gas emissions. The study also confirms that the system can be retrofitted into existing vehicle designs, making it a cost-effective and scalable solution. The adoption of this technology could significantly enhance the sustainability of hybrid vehicles, aligning with global efforts to mitigate the environmental impacts of transportation. Future work will focus on optimizing system components, exploring alternative working fluids, and conducting extended field trials to further refine and commercialize this innovative heat recovery approach. This research underscores the critical role of waste heat recovery systems in driving the transition toward more efficient and eco-friendly automotive technologies. Using this thermochemical recuperation process, the heat from the engine could be utilised to turn a working fluid into steam. As a result, the steam can be used to power a turbine, which generates electricity that can be stored in a battery pack and used as productive work in a hybrid vehicle, increasing the hybrid system's performance. The described technology may be retrofitted into practically any vehicle and improves the engine's cooling circuit, allowing it to run more effectively and lowering the vehicle's carbon footprint.

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