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Original Paper

Using Tesla turbine for waste heat recovery: Currents status and future directions

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Abstract: Waste heat recovery (WHR) has gained significant attention as a promising approach to enhance system performances and reduce greenhouse gas emissions. The Tesla turbine, known for its simplicity, reliability, good off-design performance, a simple structure, easy operation cleaning and maintenance, no blade corrosion, and low manufacturing costs, has emerged as a promising technology for waste heat recovery applications. This paper provides an extensive evaluation of the present state and prospective pathways concerning the utilization of Tesla turbines in waste heat recovery applications. The outline of Tesla turbine and its operating principles, highlighting its advantages and limitations, are introduced. A summary of the available literature on the utilization of Tesla turbines for waste heat recovery in different industrial sectors, including power plants, automotive, manufacturing, and renewable energy systems, is performed. The performance and energy conversion efficiency of Tesla turbines in these applications are critically evaluated. Furthermore, this review discusses the challenges and technical barriers associated with the implementation of Tesla turbines for WHR. It also identifies potential future research directions and suggests innovative strategies to enhance the performance and reliability of Tesla turbine-based WHR systems. These include application area in liquefied natural gas supply system and boil-off-gas return configuration. In conclusion, this review highlights the significant potential of Tesla turbines for waste heat recovery and emphasizes the need for further research and development efforts to overcome the existing challenges. The findings of this review can guide researchers and engineers in the design and implementation of efficient and sustainable waste heat recovery systems using Tesla turbine technology.
Keywords: Tesla turbine, Waste heat recovery, Bladeless turbine, Energy harvesting, Power generation

1. Introduction

Growing worldwide faces essential sustainability problems associated with energy shortage and environmental issues which demand a breakthrough in terms of energy-efficient. A large amount of engine cycles waste heat causes not only energy crisis **[1]** and extreme loss but also serious environmental pollution **[2]**. Waste heat recovery nowadays is considered to be an economic method to increase the overall efficiency of plants **[3][4]** and, thus, to lower fuel consumption **[4][5]**. Energy harvesting where low-temperature waste heat energy is converted into work or electricity, has attracted great attention of management authorities and scientists and becoming a research hotspot. Among many possible waste heats recovering method, the potential of Tesla turbine has garnered significant interest in recent years owing to its ability to achieve a moderate efficiency with low cost, reliable design and simple structure to generate electric power. And, the Tesla turbine **[6][7]** has emerged as a promising contender for replacing wasteful devices, offering the potential to enhance the coefficient of performance and minimize energy wastage **[8]**. Tesla turbine is operating as a kind of expander that is very promising for cold energy systems especially LNG systems.

The Tesla turbine is known as friction, viscous, or bladeless centripetal flow turbine and was patented in 1913 by Nikola Tesla **[9][10]**. Unlike almost kinds of turbines, the Tesla turbine has limited and specific applications **[11]**. It can be considered as

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a versatile turbine owing to its design and structure and commonly used as a steam turbine to generate electricity **[12]**. High-energy working fluids, such as those with high pressure or high velocity, hold potential for converting into electrical energy. It works on the principle of boundary layer effect, where due to air-flow, the turbine rotates and can be used not only in power plant operations but also for general applications such as expanders. In recent times, there has been a growing fascination with the Tesla turbine **[13]** due to its ability to generate power at small or micro scales, making it suitable for a wide range of applications **[14]**. This interest stems from its low-cost, reliable design, and straightforward structure, which enables it to serve as a prime mover for driving generators of various sizes. The basic waste heat recovering system using Tesla turbine can be explained as in **Figure 1**. The process of harnessing wasted heat from industrial or engineering processes and converting it into usable power or electricity is commonly known as waste heat to power or waste heat recovery.

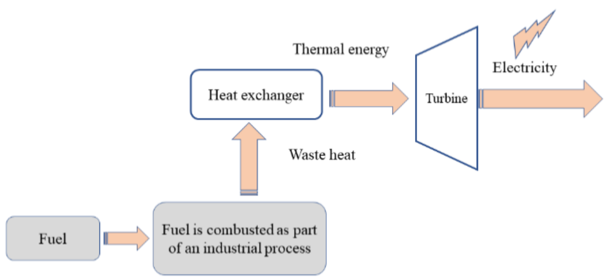

Figure 1: Typical waste heat recovering system

Numerous studies have been conducted investigating the application of the Tesla turbine for the conversion of waste heat energy into valuable power or electricity. Y. Zhao *et al.* **[15]** considered that waste heat recovery is the most important method to realize the efficient utilization of energy in the engine system. In which, the expansion device was considered as key equipment of system. Improving operation performance of expanders will increase the efficiency and power generation of system. Fenzhu Ji *et al.* **[16]** investigated the performance of the Tesla turbine small-scale waste heat recovery system of an automobile engine and shown that the total power and total thermal efficiency can be respectively enhanced by 13.2% and 5.2% in comparison with the original engine.

Sheikhnejad *et al.* **[8]** carried out the experiments on Tesla turbine with refrigeration cycle alongside with the thermo-hydrodynamic analysis of a working fluid R50 (high-pressure methane) flow in the turbulent regime and showed that Tesla turbine can be able to produce 2 kW (approximately 1440 kWh/month) in low angular velocity with R150B1 working fluid configuration, while working between input–output pressure of 60 and 30 bar. This energy which has been wasted in the conventional expansion valve of a refrigeration cycle, can be counted as equivalent to 76m of monocrystalline silicon photovoltaic solar panel and working at its maximum power in full sun hours and, enough to light up 285 LED light bulb (7 W) simultaneously. L. Tallur *et al.* **[17]** presented a performance assessment of Tesla turbines for Organic Rankine Cycle (ORC) with four different working fluids, the research presented that efficiency of the system is higher than 60% has been achieved, with the defined geometry of the Tesla turbine. L. Talluri *et al.* **[18]** also presented an experimental investigation of Tesla turbine efficiency when it's working with R1233zd working fluid and shared that they obtain a maximum net power output of 371W, a maximum shaft efficiency of 9.62% and a maximum adiabatic efficiency of 30%, it's proving the feasibility of utilizing Tesla turbines in ORC applications. The achieved results of L. Talluri research confirmed the validity and the potential of large applications of using Tesla turbine for waste heat recovery, especially in the system and fields including micropower generation, low inlet temperature and low expansion ratios. Sheikhnejad *et al.* **[19]** use Tesla turbine to be substituted the expansion valves in high pressure natural gas pipeline and got the results of 285 7W LED which is simultaneously generated by the Tesla turbine. This harvesting amount of energy is equivalent to 84.4 m2 solar panel (150 W, 15.42% efficiency) of climate condition in Canada. A. Aghagoli *et al.* **[20]** used Tesla turbine in heat pump cycle with CO_2 as a working fluid and show that the power production from the turbine, leads coefficient of performance to 5.2 occurring at P_{in} = 9 MPa, P_{out} = 4 MPa and Ω = 1000 rad/s and enhance the cycle's coefficient of performance by 16.3% in comparison with conventional cycle equipping expansion valve. G. Manfrida *et al.* **[10]** revised an original Tesla turbine and evaluated its performance with various working fluids with a specific prototype and stated that Tesla turbine can perform well with low mass flow rates and very competitive with other expanders with specific reference to efficiency. The rotational speed significantly impacts the power and efficiency of the expander. However, as a general guideline, the turbine can be appropriately sized to operate within the range of approximately 4000 to 8000 rpm. A. Mandal *et al.* **[21]** analyzed the performance of centimeter scale off Tesla turbine using numerical simulations and investigated that this turbine can provide sufficient power for micro-air vehicles applications by doubling inlet velocity. And, the velocity loss at inlet section is not be significant for certain RPM of turbine. O. K. Onanuga *et al.* **[22]** experimented with the bladeless turbine with Reynold's number Re $\leq$ 528.53, rotational speed $\leq$944.31 rad/s and its was operating with efficiency 23.9% while model efficiency is 34% and showed the improvement in bladeless turbine efficiency when compare with other expanders. L.Talluri *et al.* **[23]** successfully developed a design procedure for an Organic Rankine Cycle (ORC) utilizing a Tesla turbine. The design achieved an impressive total-to-static efficiency of 64% when operating with n-hexane as the working fluid. Li, Ruixiong *et al.* **[24]** carried out an experimental study on Tesla turbine using incompressible working medium and investigated the main causes of loss inside the turbine and calculated the partial loss of a bladeless turbine. This is a very important reference to compare with the loss of such kind expansion valves in the system. The aforementioned researches highlight numerous significant advantages of employing the Tesla turbine to enhance energy efficiency within a system. Additionally, it has been observed that low-temperature waste heat energy can achieve a higher utilization ratio through the utilization of the Tesla turbine.

Ganguly *et al.* **[25]** simulated and analyzed performance of Tesla turbine in Rankine power cycle plan and presented that the maximum rotor efficiency can be obtained 58% for 2000 MW power plant. The fuel cost for plant is observed to save up to 20% with participant of Tesla turbine.

The existing research on using the Tesla turbine has primarily focused on specific cases of waste heat recovery, lacking comprehensive investigations into the overall advantages, disadvantages, and future development trends of its application in various areas. Therefore, this literature review aims to fill this gap by discussing the various aspects of using the Tesla turbine for energy harvesting. It highlights key issues faced by the research community and provides a summary of points that can guide researchers in pursuing focused research to address these challenges. In summary, this research aims to accomplish the following objectives:

- Provide a comprehensive overview of the Tesla turbine, focusing on its operational performances, advantages, and limitations in various applications. The paper investigates the distinct characteristics of the Tesla turbine and assesses its potential for the recovery of waste heat.
- Discuss new trends and emerging developments in utilizing bladeless turbine technology for energy harvesting. The study highlights innovative strategies and advancements in the field of bladeless turbine technology that may use to increase the efficiency and performance of Tesla turbines for waste heat recovery.
- Provide suggestions for future research and development to further advance the application of Tesla turbines for waste heat recovery. The paper identifies areas that require further investigation, such as advanced materials, optimized blade designs, improved sealing mechanisms, and advanced control strategies.

Overall, this research provides a comprehensive review of the Tesla turbine's performance, examines its applications in waste heat recovery, discusses new trends in bladeless turbine technology, and outlines future directions for research in this field.

2. Tesla turbine and its application area

2.1 Basic theory of Tesla turbine

Tesla turbine as known as a viscous bladeless turbine, formed by a series of discs parallelly mounted to each other on the shaft, which is closely gap and fitted with rotating shaft **[24]**. These disks are multiple flat in parallel, thin and spaced along the shaft with thin gaps **[26]**. The turbine is mainly structured by three main components consists of discs, shaft, casing and accessories (valves and nozzles) **[23]**. The nozzles of the turbine are designed on the cylindrical casing and tangential to the shaft. The inlet enthalpy is estimated **[27]** as:

$$h_{in} = C_p \left(T_o - T_{inlet}\right) \tag{1}$$

Where T_o, T_{inlet} denote as ambient temperature and temperature of working fluid inlet the turbine (K), respectively. C_p represent as heating capacity (1005 J/g.K).

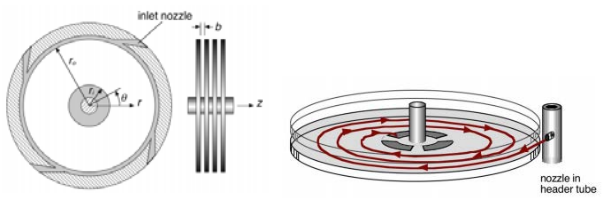

Figure 2: Configuration of a typical Tesla turbine **[18][29]**

The discharge holds are designed on the center of turbine. So that, the diameter of the disk and the inter-disc gap is mainly affected to the working performance of the turbine **[28]**. Generally, a Tesla turbine is shaped by shaft, discs, housing, collar, nozzle and bearing. The schematic of the Tesla turbine is shown on **Figure 2**.

As for its working principle, the fluid is passed into the nozzles before ejected tangentially to the rotor, the fluid velocity is significantly increased **[30]**. Subsequently, when working fluids are introduced into the narrow gaps between the discs, the relative velocity between the rotor and the working fluid generates a viscous effect in the boundary layers, resulting in the rotation of the rotor **[31]**. The geometric parameter which results from disc spacing, converts energy by the fluid in mechanical energy and generates momentum exchange of working fluid and discs, results from torque and power of the turbine. The heat generated during process of converting inlet enthalpy to work, heat and kinetic energy is estimated by:

$$q_e = C_p \left(T_{outlet} - T_{inlet}\right) \tag{2}$$

$$K_e = \frac{1}{2} V^2 \tag{3}$$

Where V denotes for outlet velocity of the working fluid.

The shaft power is generated to the rotor, the turbine can be used with function of pump or compressor. The working fluids passed nozzles and ejected into the gap with certain angle. The flow within the Tesla turbine is propelled by a pressure difference that exists between the inlet at the outer radius of the discs and the outlet at the inner radius of the discs. At the disc gap (inter-disk spacing), kinetic energy of flow of the working fluid is converted into torque and shaft power. The energy conversion is under the theme of momentum exchange of viscous drag force between flow of working fluid and both walls of each gap. The radial and a tangential velocity component using cylindrical coordinates are two main velocity profile. Torque is produced by shear stress of relative and tangential velocity component. Power is generated in rotation only. The performance efficiency of turbine can be estimated by **[32]**:

$$\eta = \frac{\dot{W}}{\dot{m}\left(h_{in} - h_{out}\right)} \tag{4}$$

Where $\dot{m}$ represents mass flow rate of working fluid, $h_{in}, h_{out}$are the total enthalpy inlet and outlet of turbine, respectively.

Besides, the torque is appeared and distributed when the tangential, relative velocity component of flow of working fluid is higher than the circumferential speed of the discs at certain radial position. And, torque can be at negative value in case of circumferential velocity of discs is higher than tangential relative velocity component of flow. Thus, process of kinetic energy conversion into mechanical energy, does not occur constantly across the radius. The flow in the Tesla turbine can exhibit either laminar or turbulent behavior, which is determined by the Reynolds number. The radial velocity component plays a crucial role in determining the flow rate within the system.

In comparisons with the conventional turbine, Tesla turbine has some highlight as simple structure, designation and maintenance cost are low, easy balancing, excellent scalability of shaft power, the competitiveness in small scale turbomachinery, robustness, operating in wide range of fluids and the self-cleaning nature due to centrifugal forces as well. W. Rice wrote in Handbook of Turbomachinery (1991) **[33]** that Tesla turbomachinery can be quietly and smoothly operation and produce nearly white noise sound signature in comparison with conventional turbomachinery, and, the turbine has competitive efficiency in comparison with miniaturized, conventional turbines in case of small shaft power scales. However, it is limited by power scales because of its restricted-on designation for the energy conversion process. So that, Tesla turbine is widely applying on small scale turbomachinery applications.

The Tesla turbines can be divided into two categories according to the inlet geometry: nozzle type and volute Tesla turbine type **[34]**. The simple design of the Tesla turbine, combined with the parallel flow of the fluid along the turbine disks, offers a notable advantage over conventional bladed turbines. This design allows for the presence of abrasive particulates and water droplets in the working fluid without the risk of direct impacts that could potentially lead to additional wear and damage to the disks. This characteristic of the Tesla turbine allows it to effectively utilize a wide range of fluids without causing any damage to the blades, thereby offering distinct advantages over traditional turbine designs. Besides, the Tesla turbine shows minus points such as: Efficiency of the turbine is depending on in and outflow of the working fluids, use only for medium and high-power applications, the flow rate must be small for the high efficiency and narrow range of applications as well.

Figure 3 below is a comparison among three basic kinds of turbines. The Tesla turbine (green line) is a highlight with rotational speed and quasi-independency of pressure ratio with rotational speed, proper of dynamic machines. The disadvantage of Tesla turbine can be seen as lower power generation (less than 3.10^4 W) in compared with volumetric expanders and axial & radial turbines.

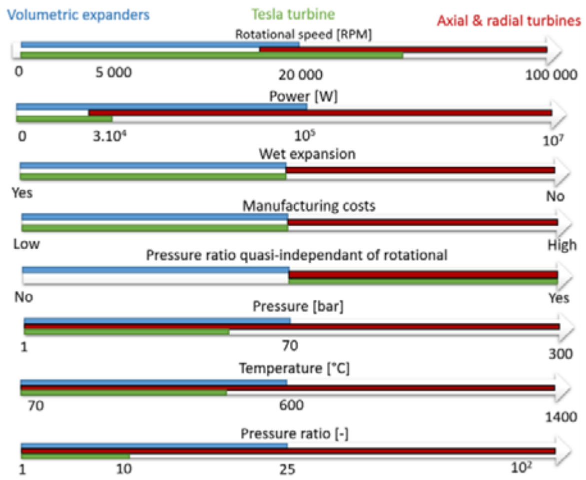

Figure 3: Characteristics comparison among some kinds of turbines **[18]**

2.2 Application areas

Initially, the Tesla turbine is not popular as other turbines **[35]**. However, with the above structure aspects, working principles and performance characteristics, the Tesla turbine is able to use in more and more wide range of applications and effectively serves to compensate for the world's future energy crisis **[31]**. Different from other kinds of turbines, the Tesla turbine can be used in working fluids and multiphase without damage **[23]**. The mains areas of Tesla turbine applications include waste heat recovery, renewable energy resource, distributed generation system, irrigation channels and hybrid electric vehicles as well **[36]**. As the world trends moving towards renewable sources, Tesla turbine perfectly fits future vision in using renewable fuel at multiple locations and competitive cost as well. However, its major drawback is limited applications over conventional turbines because of their compact and small size.

Due to its exceptionally high efficiency, the Tesla turbine holds great potential to significantly enhance the efficiency of low-performing plants. Specifically, the Tesla turbine can be effectively employed in conjunction with waste heat from thermal power plants, as well as heat obtained from cycles or fuel cells, to generate electricity. Consequently, the utilization of the Tesla turbine for waste heat recovery has garnered considerable attention from scientists due to its substantial impact on performance efficiency and environmental considerations.

3. Current status of using Tesla turbine for waste heat recovering

Waste heat recovery is playing a very important role in improving energy utilization and efficiency of all system. A diverse array of energy systems and waste heat sources exist, including gas and steam turbines, internal combustion engines, geothermal heat, industrial and household waste heat, biomass, solar heat, and more **[37]**. Waste heat technologies contribute much to increasing system efficiency and reducing the fuel consumption of the system.

The turbine's bladeless design and unique flow characteristics allow for efficient energy conversion, making it well-suited for capturing and utilizing waste heat from various industrial processes **[38]**. In terms of application areas, the Tesla turbine has been successfully employed in diverse sectors such as power plants, automotive systems, manufacturing processes, and renewable energy systems. These applications showcase its versatility and effectiveness in capturing and converting waste heat into usable energy **[39]**.

Furthermore, the Tesla turbine offers advantages over conventional radial or axial flow turbines in waste heat recovery scenarios **[40]**. The compact size, simplicity of design, and capability to accommodate various working fluids make the Tesla turbine an appealing choice for integration into existing systems without the need for significant modifications.

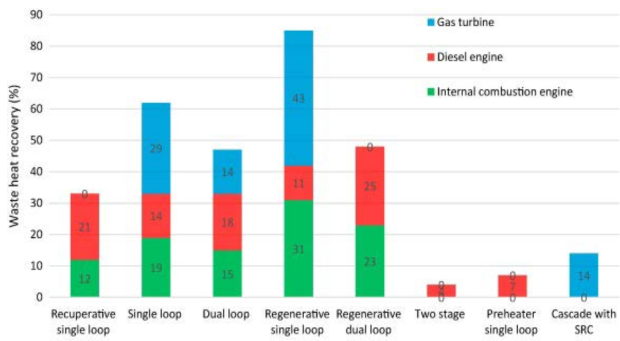

Figure 4: Waste heat source **[37]**

Among of various components in thermodynamics systems, the expander is lighting as the most significant device for waste heat recovery. And as said, the Tesla turbine offers an appropriate option in terms of expander as better characteristics than conventional expander. Numerous researchers have been investigating the feasibility of employing Tesla turbines in small-scale waste heat recovery systems. In this paper, the thorough examination of recent studies that have explored the application of Tesla turbines in various typical systems.

3.1 Tesla turbine as an expander on ORC

The ORC has been applied for decades for recovering waste heat from industrial processes and produce power. Generally, technologies for improvement the system performance can be divided into three main areas: configurations, working fluids and working conditions **[37]**. As for the ORC system, the waste heat is recovered mainly by power output of the turbine. So that, to maximize the power output, it is necessary to optimize the operation and cost (manufacturing and maintenances) **[41]**. One of the common method to increase power output and efficiency of ORC is increasing the operation performance of turbine **[42][43]**.

Figure 5 shows the schematic diagram of general ideas of using Tesla turbine as an expander on ORC system. The system consists basically Tesla turbine as an organic expander, condenser, working fluid pump and evaporator. In general, the working principles of the system can be described as follows: the working fluid in liquid form is pumped from the condenser into the evaporator. And, the heat exchange will be occurred here and transfer heat to the working fluid and turned it into saturated or superheated vapor. Then, the organic superheated vapor expands in the Tesla turbine (as an expander) for producing electric power. Subsequently, the exhaust organic vapor is expelled from the Tesla turbine and condensed back into a liquid state in the condenser through the use of cooling water.

In Tesla turbine, process 4-5 (isentropic process) can be calculated by:

$$w_T = \dot{m}_{wf}(h_4 - h_{5s})\,\eta_T \qquad (5)$$

Which, $h_{5s}$the isentropic enthalpy of the exhaust organic vapor at outlet of Tesla turbine and η_T is its efficiency.

Rusin *et al.* **[32]** analyzed and optimized the operation of Tesla turbine in a ORC and compared with experiment results. The research results revealed that Tesla turbine can support to increase from 9-17% of overall efficiency of system.

It is noteworthy to mention that the Tesla turbine exhibits the potential to attain even greater efficiency than the value documented in the research, assuming there are no constraints imposed by constructional limitations or parameter restrictions.

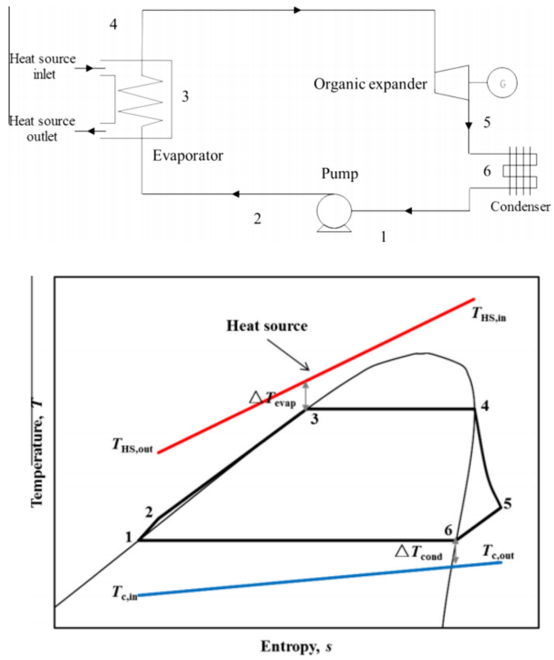

Figure 5: Schematic diagram of Tesla turbine as an expander on ORC system

Song *et al.* **[44]** analyzed the application of Tesla turbine in small scale size of ORC. The various of configuration and working fluids are tested to examine the ability of generation power of Tesla turbine and proved that Tesla turbine is very potential for small scale ORC. With R245ca as working fluid, Tesla turbine can generate a significant net power output and thermal efficiency in small scale system and got 4% ORC efficiency, with 1.25 kW. The efficiency of the Tesla turbine down at lower evaporation temperature and then increases with the increment of the evaporation temperature (**Figure 6**).

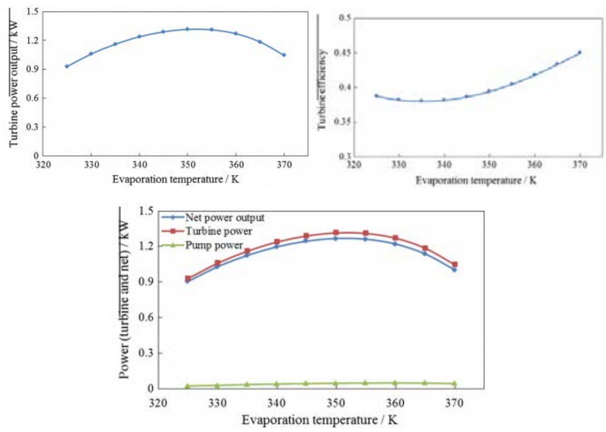

Figure 6: The variation of power output and efficiency of Tesla turbine in ORC **[44]**

Indeed, the heat exchange that occurs in the evaporator of the Organic Rankine Cycle (ORC) system fluctuates in accordance with the outlet temperature of the heat source. Thus, with each separate heating source temperature, a proper evaporation temperature of the ORC system should be carefully calculated to determine the optimum working area of Tesla turbine and ORC system as well. The power output of the Tesla turbine is dependent on both the mass flow rate of the working fluid and the specific power output. When the evaporation temperature is higher, it leads to a greater power output per unit mass of the working fluid. Additionally, the mass flow rate of the working fluid directly influences the overall power output of the ORC. With an increasing direction of evaporation temperature, the turbine efficiency will first down and up when evaporation temperature reaches 335K. The significant impact of evaporation temperature on the performance of the ORC system is clearly demonstrated by the difference in turbine efficiencies observed at 335 K and 370 K, which amounts to approximately 0.05. The tendency of power of Tesla turbine and system is the same, at the evaporation temperature of 350 K, the ORC system yields 1.27 kW and at the highest net power output and thermal efficiency of the system reaches 0.043. This proves that the Tesla turbine generates a significant net power output and thermal efficiency in small scale system.

In case of upgrading the Tesla turbine with low specific speed n_s (0.001-0.005) and high specific diameter D_s (20-50) and shown very low (0.01-0.1) of right range of flow coefficient for optimum rotor efficiency and increase power output (0.05-0.2). The turbine was sized to effective work around 4000-8000 rpm **[10]**.

In case of, R1233zd(E) as the working fluid, the results obtained the maximum the net power output of ORC system at 371W and the shaft efficiency and maximum adiabatic efficiency was at 9.62% and 30% respectively. This affirmed effectively of utilizing Tesla turbines in ORC applications better than other kinds of expander **[18]**. The test bench of this system is fully described in **Figure 7**.

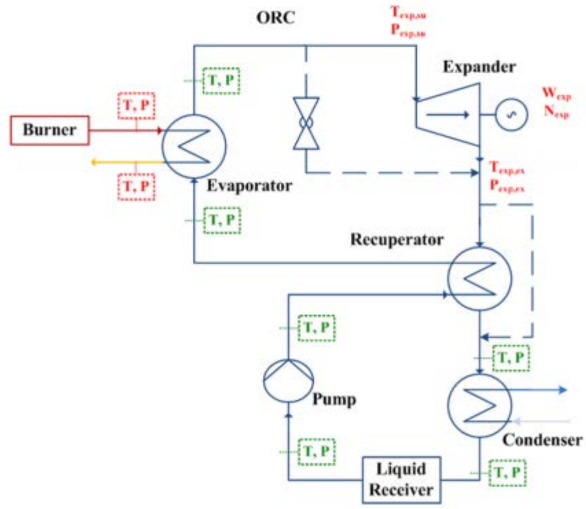

Figure 7: Schematic diagram of test bench of Tesla turbine in ORC with R1233zd(E) **[18]**

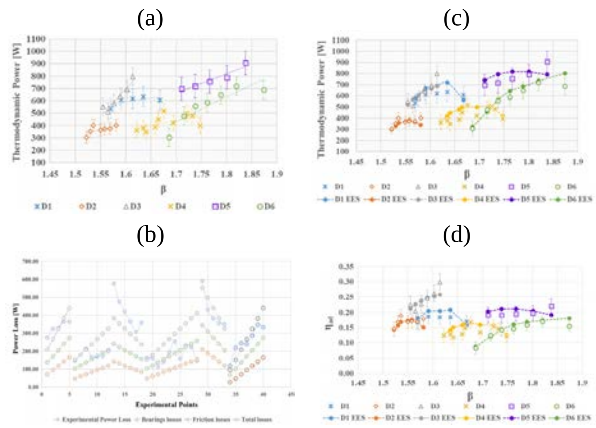

Figure 8: The parametric study with varies of conditions to the powers and efficiencies **[18]**

Figure 8(a) shows the relationship between thermodynamic power output and expansion ratio. Thermodynamic power reach 906W as the maximum obtained value together with 0.299 kg/s of mass flow rate and 44°C of superheating level at 5000 rpm rotational speed. The obtaining highest power output conditions at high value of superheating levels (data D3 and D5) and high value of mass flow rate conditions (D1 and D6). **Figure 8(b)** describes the experimental points and power losses of the turbine in comparison with the predicted bearing losses and total of bearings losses and friction losses of the Tesla turbine because of the relationship between the electromagnetic couplings. And, Figure 8c, d, show deviation of 8% of experimental power and efficiency and the corresponding simulated values; the Pearson coefficient of power and efficiency are 0.95 and 0.92 in respectively. The coefficient of correlation of power and efficiency are 0.89 and 0.85. Research obtained a maximum of 9.62% of shaft efficiency and 50% of mechanical efficiency (including generator and torque meter losses) of ORC Tesla turbine.

L. Talluri *et al.* developed a Tesla turbine for ORC applications and achieved a total to static efficiency of lower size and larger size version are 52% and 64% respectively **[23]**.

The Tesla turbine exhibited its best performance at an optimal rotational speed and low inlet pressure, with distinct values for power output and efficiency. And, the inlet temperature has not much inflected to the performance of the Turbine. The optimization of turbine efficiency relies heavily on the channel height and the ratio of the inlet and outlet rotor diameters. These parameters play a crucial role in determining the overall efficiency of the turbine.

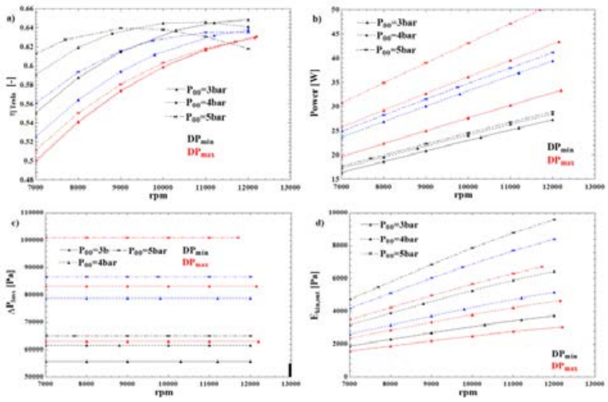

Figure 9: Operating map of Tesla turbine in ORC **[23]**
a) efficiency, b) power output, c) stator–rotor losses, d) kinetic energy

Furthermore, B. Peris *et al.* **[45]** evaluated ORC system using a turbine as an expander for harvesting low grade heat sources and resulted that performances ORC system was improved for higher thermal oil temperatures, capturing more thermal power, and obtaining better cycle efficiencies. They received maximum gross electrical efficiency, heat source temperature as 12.32% and 155ºC respectively. Furthermore, the Tesla turbine is well-suited for power applications utilizing low-grade heat sources. It has been found to exhibit an electrical isentropic effectiveness of around 65% when operated at an optimal pressure ratio of approximately 7.

Figure 10(a) illustrates the gross electrical efficiency of the cycle, indicating that the efficiency tends to increase with the pressure ratio. It reaches a maximum value of 12.32%, which is higher for higher thermal oil temperatures. **Figure 10(b)** compares the cycle efficiency with the ideal Carnot efficiency and indicates that the efficiency trend of the cycle becomes attenuated for the highest values. **Figure 10(c)** is justified this effect in the case of observing referred to the expander. The electrical isentropic effectiveness of the turbine reaches a maximum value above 65% when operating at a pressure ratio around 7, as imposed by the expander 6. This operating range is considered suitable for power applications utilizing low-grade heat sources. This

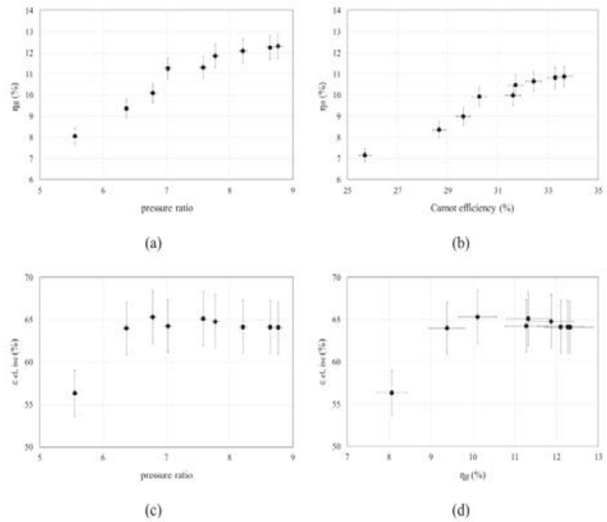

Figure 10: Thermodynamics performance of: (a) gross, (b) net, (c) expander, (d) cycle **[23]**

also proved the energy losses produced through conventional expanders.

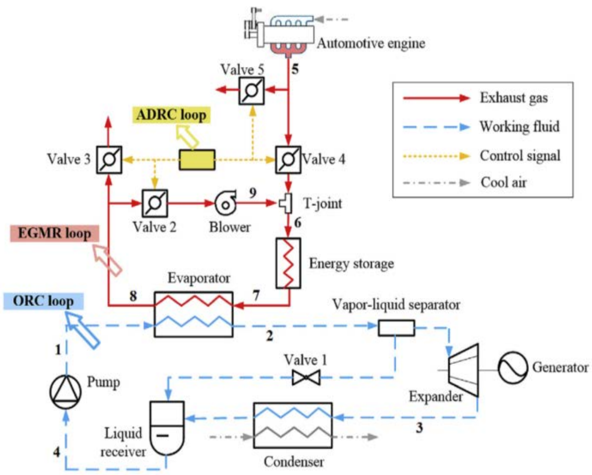

Figure 11: the schematic diagram of ORC for waste heat recovery **[46]**

The Tesla turbine has also experimented in the ORC combined system including three main loops of ORC, EGMR (Exhaust Gas Mixture Recirculation) and a control loop (**Figure 11**). In which, the ORC is mainly designed for waste heat recovering from the EGMR which exhausted temperature varies between 300ºC and 500ºC. The overall energy efficiency of the system increases 0.9% for conventional ORC and 1.5% for the ORC-EGMR system. It is proved that using a Turbine instead of a conventional expander bring much more benefit to the working efficiency of the system **[46]**.

3.2 Tesla turbine in refrigeration cycle

Among the various components acting as throttle valves for a refrigeration system, Tesla turbine shows a high potential for recovery waste energy and transfer it to power or work. In 2019, Yahya Sheikhnejad *et al.* **[8]** introduced the Tesla turbine to substitute the wasting devices of the refrigeration system to increase the coefficient of performance and decrease waste energy of the system. It is effective operating to reduce refrigerant pressure before it enters the evaporator without compromising the system output quality.

Sheikhnejad analyzed thermo-hydrodynamic characteristics of R50 (high-pressure compressible methane) flow in the turbulent regime and proved that the Tesla turbine can be able to produce up to 2 kW (1440 kWh per month) in low angular velocity with R150B1 configuration. Those energies have been already wasted in expanders of the conventional refrigeration systems.

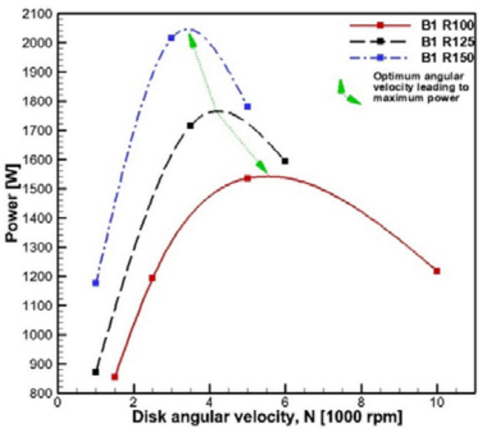

Figure 12: Dependency of power on disc angular velocity in different turbine dimension **[8]**

Among three curves of geometry configuration (disc gaps, outer diameter), the “optimum speed” where the Tesla turbine generated power becomes maximum, will be set up. This optimum speed will vary depends on the dimension (configuration) of the Tesla turbine.

A novel Turbo expander based on the Tesla turbine was innovated and experimented to the expansion of refrigeration cycle for enhancing overall efficiency of the system and waste heat recovery as well **[47]**. This Tesla turbine is using steam as a working fluid and comprise of a single passage between two discs. Due to dense cloud of liquid droplets in the flow between the discs, considerably, it has produced pressure decrease through the rotor, lead to delay the phase change and a decrease in the performance of Tesla turbine. The purpose of this experiment is to shortly start and confirm the size of droplets and initial modeling as well. This is expected to enhance the efficiency of the Tesla turbine as well as the performance of the refrigeration system.

3.3 Tesla turbine in micro combined heat and power system

The Tesla turbine for micro combined heat and power system utilizing low-grade heat sources which archived 1.5 kW electric power and 6.3% of turbine efficiency at 4 of pressure ratio. The parametric study has also shown that an isentropic efficiency of 19.6% and a turbine efficiency of 6.3% and performance of Tesla turbine with more efficient and economical than conventional micro-turbines in using low-grade heat sources areas **[48]**.

The testing system is made from the boiler and small incinerator’s on-off valve, Tesla turbine, a 5 kW-class single-phase generator; and 20 parallel bulbs (100 W for each) as load. The thermal energy source was applied the exhaust waste heat from the small incinerator. The performance of the Tesla turbine working with waste heat using from small-scale incinerator was showed in an experimental result that includes 0.1 kg/s of lower mass flow rate, 419.45 K (146.3°C) of inlet temperature and 0.43 MPa (3.3 bar) of inlet pressure. The collected data and comparison between theoretical and practical were showed in **Table 1**.

Table 1: Comparison of theorical and practical results **[48]**

Parameters	Calculation	Practical	
		With common pressure ratio	Pressure ratio
Mass flow rate, kg/s	0.0856	0.0801	0.1
Turbine inlet pressure, MPa	0.35	0.35	0.43
Turbine exit pressure, MPa	0.1	0.107	0.108
Work of turbine, kW	4.84	4.25	4.65
Power, kW	2.32	1.15	1.50
Isentropic efficiency, %	25.15	26.0	19.65
Efficiency of turbine, %	12.06	7.06	6.3

Figure 13 shows a decreasing trend of efficiency in line with the increasing pressure ratio. This can be explained as the increasing pressure ratio lead down loss of the mass flow rate. So that, more loss will lead down the turbine power relative to the increasing input energy as well and become the largest factor to reduce efficiencies.

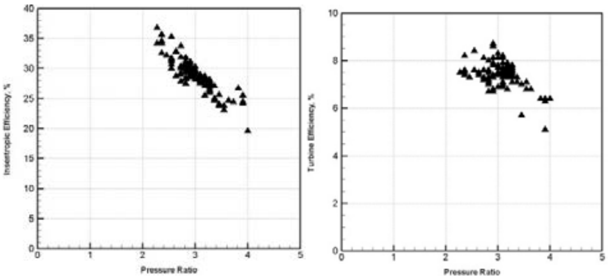

Figure 13: Isentropic and turbine efficiencies of Tesla turbine for pressure ratio **[48]**

The Tesla turbine performed 5-10% efficiency at 4 kW of electrical output, and 3% less efficiency at 3 kW of electrical output of the heat pipe-turbine. This is proved that Tesla turbine can bring greater economic benefit than the conventional one.

3.4 Tesla turbine in engine system

Normally, the exhaust gas from engines counted to 30–35% of total energy **[41]**. So, engine system is potential for heat recovery and such kind of energy should be utilized by novel solutions such as compressor-exhaust gas turbine group, ORC system, thermo-electric generator and so on. However, for enhancing efficiency of system, the waste heat technologies for engine system should adapt the following requirements **[49]**:

- Highlighting efficiency in waste heat using;
- Easy and safe operating;
- High ability on response with sink properties and transient heat source;
- Good adaptable to the changing operation regime of the engine;
- It can be easily integrated with others power systems;
- Enough power density for supplying large power as required.

Ji Fenzhu *et al.* **[16]** investigated the performance of the Tesla turbine in engine waste heat recovery and stated that the operation of the Tesla turbine was tightly related to the rotation speed and fit to work at 500 rpm-2500 rpm (low and medium rotation speed). The power and thermal efficiency of system increased by 13.2% and 5.2% respectively, on average compared with the original engine.

The general schematic of small-scale engine waste heat recovering using a Tesla turbine is described in **Figure 14** below. The working principles as follows: The coolant liquid is supplied to the heat exchanger after exiting the engine. After absorbing heat from the heat exchanger, the liquid flows into the Tesla turbine, where it generates kinetic energy that is subsequently converted into electric energy by a generator. The coolant liquid is then directed to a radiator for cooling, achieving the desired temperature before being fed into the water tank. From there, it is pumped into the cylinder cooling jacket, completing the cycle. This system offers several advantages, including a simple structure, low noise level, and cost-effective manufacturing. This system uses a Tesla turbine with number of discs, outer radius, outer diameter, gap and incident angle are 20, 40mm, 12mm, 0.7mm and 10o respectively. The testing results showed that the experimental results are 8.5% and lower than the simulation and the theoretical results are 12.3% and higher than the simulation results on average and the experimental pressure drops 9.1% higher than the theoretical ones.

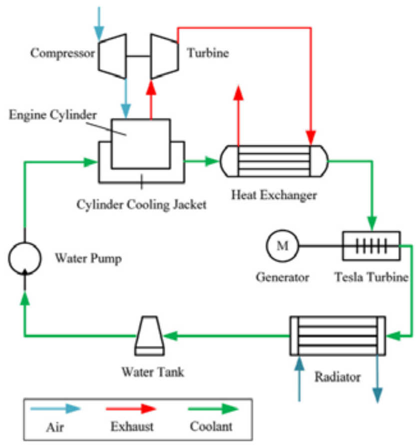

Figure 14: Schematic of using Tesla turbine for engine waste heat recovery **[16]**

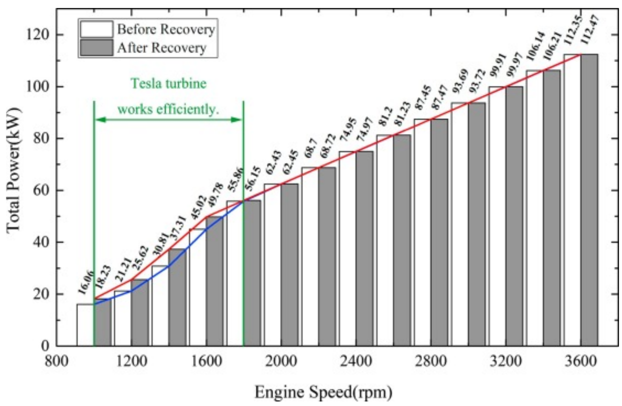

Figure 15: Comparison of the total power output between the system before and after implementing the recovery process **[16]**

Figure 15 is a comparison of power before and after recovery. It showed that total power is enhanced at the range of 1000 rpm

- 1800 rpm of engine speed, and can be raised by 13.2% on average, despite the improvement of that is not obvious above 2000 rpm, those values are in comparison with the original engine. This clearly showed that the Tesla turbine reflected a greater capacity of energy conversion at the range of low rotation-speed.

The Tesla turbine demonstrates effective performance at low and medium rotation speeds. Due to the structural characteristics of the Tesla turbine, working fluids with higher viscosity, larger coefficients of thermal expansion, and lower specific heat capacity are most suitable. The integration of the turbine into an ORC system for waste heat recovery in a diesel engine has resulted in notable enhancements in the overall thermal efficiency. The dual or multi-loop ORC system achieves thermal efficiency enhancements of up to 10% and 60-90% respectively when compared to the 10-25% thermal efficiency of a single-loop ORC system **[41]**.

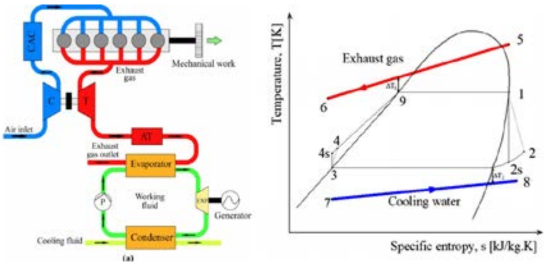

Figure 16: Configuration of engine -ORC system **[41]**

In view of the fact that, the system for waste heat from engine much depends on its exhaust gas components because of different of specific heat of each component. This will be much effected to operating conditions and efficiency of Tesla turbine. The possible efficiency ranges for different waste heat recovery systems from engines from 5% to 37% **[49]**.

4. Summary, future directions and concluding remarks

While the current status of using the Tesla turbine for waste heat recovery is promising, there are still challenges to overcome. These include addressing blade erosion, improving flow control, and optimizing system integration. Ongoing research and development efforts are focused on enhancing the turbine's performance, durability, and reliability to further optimize its application in waste heat recovery. Various studies have pointed potential outcomes for the future of Tesla turbines. As large losses occurring in small scale system of conventional turbines, the Tesla turbine running with loss inducing forces to convert and generate useful work and power. Almost of studies on Tesla turbine have been focused on micro and small-scale system applications. With many advantages on simple structures, versatile design, low manufacturing cost, will make it a favored and can be used in a wide range of applications. Tesla turbine is a promising alternative where conventional turbines prove impractical. The properly selected Tesla turbine may improve overall system efficiency, reduce the investment and operations cost and enhance the eco-friendly performance.

Our earth is facing up with global energy crisis, renewable energy is more and more playing an important in energy strategy. Natural gas (NG) characterized by high exergy, cold store and many priorities for serving as the best candidates for waste energy harvesting. However, during NG transfer and usage, there is a large amount of exergy loss occurring in the city gate station, expansion valves, and piping system. Almost industry including city gate station, Organic Rankine System, Boil-off-gas handling system and letdown stations still have used regulators/ expansion valves and throttling valves to reduce pressure **[19]**. But, the large amount of exergy loss occurring in conventional expanders causes the down of energy using performance and economically of system. With the better structure characteristics than other conventional turbines, the Tesla turbine show potentials on working with varieties of fluids, low cost, high efficiency. The Tesla turbine will be very promised on waste heat harvesting and integrated with an AC or DC generator to produce electricity.

Y. Sheikhnejad *et al.* **[19]** innovated a novel of Tesla turbine as an alternative to expanders of city gate station on high pressure NG pipelines and proved that extracting mechanical work from natural gas lead down both pressure and temperature. So that, natural gas has more ability to absorb more heat from the environment and transfer it to useful direct mechanical power.

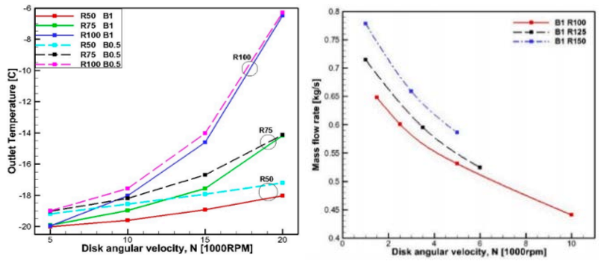

Figure 17: Thermodynamics analysis on geometry of Tesla turbine on outlet temperature and mass flow rate

As seen in **Figure 17**, optimum angular velocity will produce maximum output power and a larger Tesla turbine will have a bigger outlet temperature. Numerical studies results showed the huge capacity of electricity generated (1440 kWh/month and equal to $2846 per year). This amount of energy harvested from waste heat that already loosen by other kind of expanders.

In summary, this paper has presented an extensive examination of the present state and future prospects of employing the Tesla turbine for waste heat recovery (WHR). The analysis and findings presented herein shed light on the advantages, limitations, and potential of this innovative turbine technology in the field of WHR. The review revealed that the Tesla turbine exhibits unique operational characteristics, including its bladeless design, high thermal efficiency, and ability to handle various working fluids. These features make it a promising candidate for WHR applications. By harnessing waste heat from industrial processes and converting it into usable energy, the Tesla turbine offers a sustainable solution for improving energy efficiency and reducing greenhouse gas emissions. Through a detailed examination of the existing literature, the review identified several typical application areas where the Tesla turbine has been successfully employed for waste heat recovery. These areas include power plants, automotive systems, manufacturing processes, and renewable energy systems. The analysis showcased the potential of the Tesla turbine in each application domain, highlighting its superior performance compared to traditional radial or axial flow turbines. The turbine's efficiency, compact size, and adaptability to varying working conditions make it an attractive choice for WHR across different industries. Looking towards the future, this review identifies several key areas for further research and development. These include advancements in turbine design, optimization of blade configurations, exploration of advanced materials, improvement of sealing mechanisms, and development of advanced control strategies. Addressing these aspects will enhance the performance, durability, and reliability of Tesla turbine-based WHR systems. The following are the key concluding remarks:

1. The Tesla turbine, with its remarkable structural and economic characteristics, is a wise alternative to conventional expanders within a system. However, due to its specific structure and operational requirements, the Tesla turbine is most suitable for implementation in small-scale systems.
2. The use of the Tesla turbine as a substitute for the expansion valve in refrigeration systems shows promise. By incorporating the Tesla turbine into a refrigeration system, it not only reduces heat loss but also generates power that can be supplied to the system.
3. Various parameters, including the characteristics of the working fluid, operating conditions, and the geometry of the turbine discs, can significantly impact the efficiency of the Tesla turbine and its overall cycle performance.
4. The natural gas system, with its abundant cold energy potential, holds great promise for harvesting significant amounts of wasted energy through its pipelines and expansion valves.

This study aims to outline the main technologies for utilizing the Tesla turbine as a waste heat recovery device. By highlighting the advantages and significant potential of the Tesla turbine as a viable substitute for expanders within the system, this research not only demonstrates its capabilities but also opens the door to potential future applications of Tesla turbine technology. A future study is planned to analyze the utilization of the Tesla turbine in liquefied natural gas (LNG) supply systems, with the objective of showcasing its potential in this particular field. Aiming to investigate and evaluate the feasibility and advantages of incorporating the Tesla turbine in LNG supply systems, emphasizing its potential benefits and contributions to improved efficiency and energy recovery.

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Author Contributions

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