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Potential Improvements to Increase Energy & Thermal Efficiency in Nuclear Power Plants

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ABSTRACT

This study aims to introduce new innovations in the nuclear energy generation industry by referring to some existing possible solutions, prototyped by professionals, and 2 new innovations developed by the author. This paper has concluded the most suitable region to place a turbine in a pipe, and the approximate electricity and revenue generation by employing a system of pipes fitted with turbines. Furthermore, this paper talks about the disadvantages of such systems and offers solutions for the maintenance of the same.

Keywords: Nuclear energy, turbine, revenue generation, sustainability, nuclear fission, power plant, safety measures.

INTRODUCTION

This study aims to provide insight into possible and existing innovations in the nuclear energy generation industry. In thermodynamics, thermal efficiency is a dimensionless performance measure of a device that uses thermal energy, such as an internal combustion engine, steam turbine, steam engine, boiler, furnace, refrigerator, ACs and more (Wikipedia, 2023). On the other hand, energy efficiency is the process of reducing the amount of energy required to provide products and services (Wikipedia, 2023). Such efficiency is crucial to ensure the economic and environmental sustainability of nuclear power plants. This can be done by utilizing the flow of coolants to generate electricity and properly utilizing steam at its maximum efficiency. These solutions are discussed in detail in the paper. This study also looks into some established innovations such as sodium-cooled reactors, molten salt reactors, and very high-temperature reactors. Parallelly, this research paper also introduces 2 ways to increase energy generation and saving efficiency of the power plant, whilst looking into the disadvantages and maintenance of the same.

How does it work?

According to the Emirates Nuclear Energy Corporation (2022), a nuclear reactor produces electricity in much the same way other power plants do. The chain reaction produces energy, which turns water into steam. The pressure of the steam turns a generator, which produces electricity.

A Pressurized Water Reactor (PWR) is the most popular type of nuclear reactor. The high pressure in the reactor prevents water in the reactor vessel from boiling. The super-heated water is carried to a steam generator, which is made up of many small pipes. The heat in these pipes is used to turn a second, isolated, supply of water to steam, which is in turn used to drive the turbine. The water from the reactor is pumped back into the reactor vessel and reheated. The steam from the turbine is cooled in a condenser and the resulting water is sent back to the steam generator (Emirates Nuclear Energy Corporation, 2022).

Nuclear Fission

Fission is the process of splitting a nucleus in two. Inside each uranium fuel pellet, there are millions of uranium nuclei. When these nuclei are split, a huge amount of energy is released. Some of this energy is from radiation, but the biggest source is kinetic energy. This energy produces heat inside a reactor, which in turn is used to generate steam, and ultimately creates electricity (Emirates Nuclear Energy Corporation, 2022).

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Existing Purpose of an HVAC System in a nuclear power plant

According to MarketScale (2018), HVAC plays an essential role in ensuring the safety and smooth operation of nuclear power plants. Some of the most important functions include:

1) Maintaining ambient conditions within acceptable limits of temperature and humidity, and control contamination.
2) Protect staff and equipment from specific risks inside the buildings, such as explosions or fire.
3) Ensure ambient conditions in order to prevent the degradation of machinery.
4) Monitor the release of air from the controlled areas and contain any radioactivity that might be released in the event of a malfunction, failure, or accident.

Examples:

1) Efficiency Particulate Absolute (HEPA) filter for particle removal. Each filter tested is required by regulation to remove 99.97% of fine dust particles (Wattco, n.d.).
2) Activated charcoal filters remove radioactive substances such as iodine-131, which causes thyroid cancer.

What is the problem?

Nuclear energy, even if it is one of the most sustainable sources of energy in the world, is not problem-free; this is because of the following reasons as per Clark (2019):

1) The condensing processes in the power plant release a lot of steam into the atmosphere, slightly raising the temperature of the surroundings.
2) To replace this lost water, which is also known as the "coolant" in this case, additional water is drawn from an external water source such as a lake or an artificial reservoir. This process gradually leads to qualitative water pollution and degradation.
3) Complex energy-consuming systems are required to maintain various factors such as temperature, pressure, humidity, etc.
4) Hot water, when released into water bodies, negatively impacts aquatic life.

Nuclear energy produces radioactive waste

Materials such as spent nuclear fuel can remain radioactive and dangerous to human health for thousands of years, and also require a lot of money to store properly (U.S. Energy Information Administration, 2022).

Existing Innovations

According to the US Office of Nuclear Energy (2021), the following innovations are likely to come up around 2030:

Sodium-cooled fast reactor

Sodium-cooled fast reactors (SFRs) use liquid metal (sodium) as the coolant instead of the water normally used in US commercial power plants (Office of Nuclear Energy, 2021). This allows the coolant to operate at higher temperatures and lower pressures than current reactors, making the system more efficient and safer. SFR also uses the fast neutron spectrum. That is, neutrons can cause fission without first slowing them down, as is the case in modern nuclear reactors. This will allow SFR to generate electricity using both fissile material and spent fuel from current reactors.

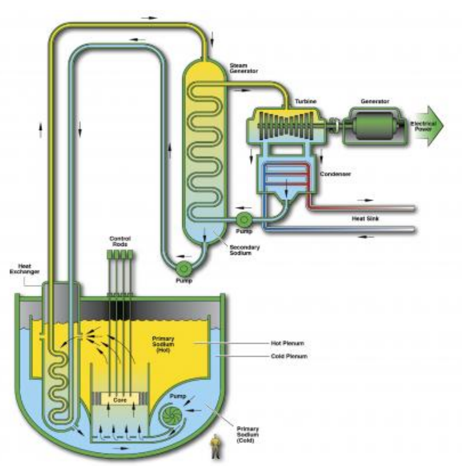

Figure 1: Schematic Diagram of a Sodium-cooled Fast Reactor (SFR)
Source: Office of Nuclear Energy (2021)

Very High-Temperature Reactors

High-temperature reactors are designed to operate at high temperatures where they can be cooled by flowing gases and generate electricity very efficiently. Hot gases can also be used in energy-intensive processes that currently rely on fossil fuels. High-temperature reactors offer excellent safety features and are easy to build and inexpensive to maintain.

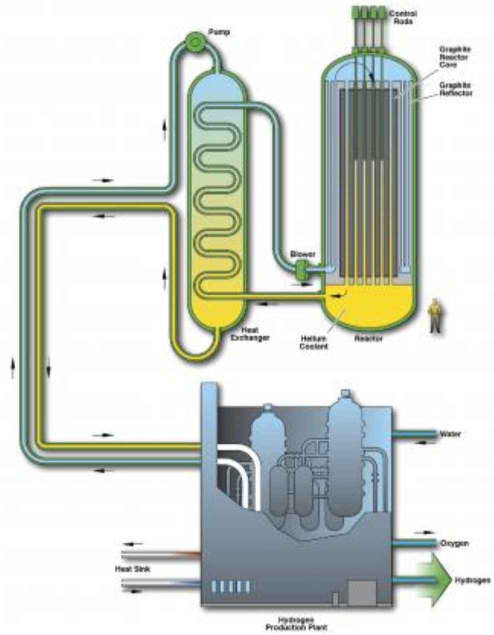

Figure 2: Schematic Diagram of a Very High-Temperature Nuclear Reactor
Source: Office of Nuclear Energy (2021)

Molten salt reactors

A molten salt reactor (MSR) uses molten fluoride or chloride salts as a coolant. The coolant can either flow over solid fuel as in other nuclear reactors or dissolve the fissile material directly into the primary coolant so that fission heats the salt directly. MSRs are designed to use less fuel than other types of nuclear reactors and produce short-lived radioactive waste. They have the potential to transform the safety regime and economics of nuclear power generation by processing fuel online, removing waste, and adding new fuel without long refueling outages. Their operation could be tailored to burn plutonium and smaller actinides efficiently, potentially allowing MSRs to consume waste from other reactors. The system can also be used for power and hydrogen production, water desalination, and many other energy-heavy industrial processes.

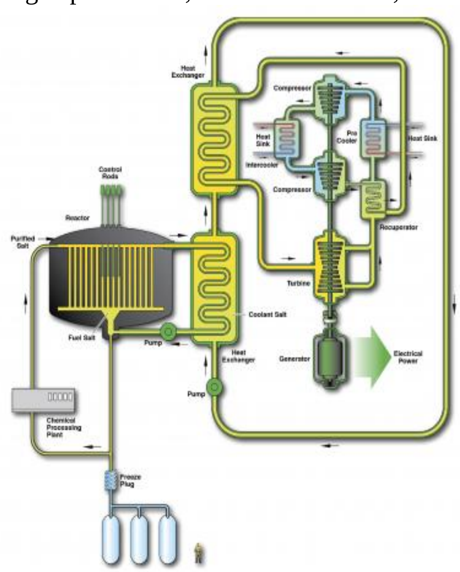

Figure 3: Schematic diagram of a Molten Salt Nuclear Reactor
Source: Office of Nuclear Energy (2021)

Proposed solutions

1) **Generators in coolant pipes**

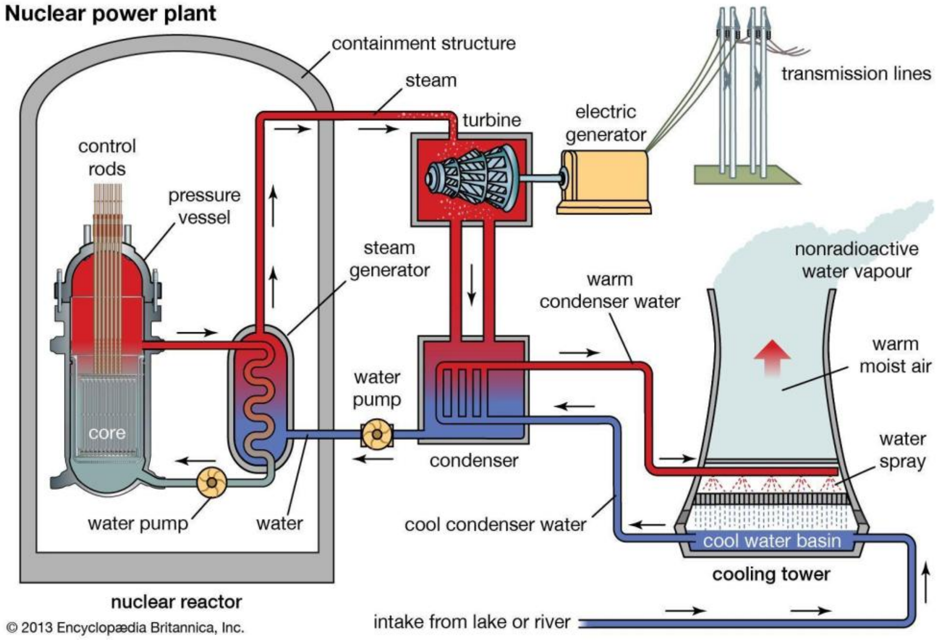

Figure 4: Schematic Diagram of a Nuclear Power Plant
Source: Encyclopedia Britannica (2023)

A nuclear power plant has two condenser units, acting as heat exchangers to condense the steam back into a liquid state after it passes through the turbines. It is imperative that the water/steam in its closed-loop system remain free of any contaminants to maintain integrity.

According to Teresa Hansen (2007), the functions of a condenser include:

1) Condense and recover the steam that passes through the turbine (Condensers are used in all power plants that use steam as the driving force)
2) Maintain a vacuum to optimize the efficiency of the turbine.

Figure 5 - The BN-800 reactor at the Beloyarsk Power Station in Russia
Source: IAEA (2020)

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How will it be done? – An idea/possibility

The main function of the pipe carrying the coolant in a condenser in a nuclear power plant is to cool and condense the steam that drives the turbine. This is done by using water directly from a reservoir, such as a lake, or using the power plant's own artificial reservoir. In the second case, cooling towers are required to cool down the water that condenses the steam, and ensure a continuous and closed cycle of water. This water runs at a high pressure and velocity, in a properly designed pipe. This flow of water, not just in the condenser pipes, but in any pipes, can easily be utilized to generate electricity. However, the temperature and pressure of water in the primary and secondary loops in the plant are very high, which might make it inefficient to install turbines in the pipes. These turbines can also be made sustainable by using biomass–derived substances or 3D printing using biodegradable plastic (Bellini, 2023). If not the turbines, energy can also be generated by using piezoelectric sensors in air vents and water pipes. These piezoelectric sensors generate energy from pressure exerted by the fluid on the walls of the pipe. This solution has been tested and proven to be efficient (Gkoumas, 2017)

Advantages

One of the main advantages of this design is the generation of more electricity. This electricity can then be supplied for multiple purposes in the power plant, such as temperature regulation, valve operation, ventilation, etc. It can also be stored in batteries or UPS and then supplied for various purposes to other infrastructure. Another frequently asked question about such a setup is, "Will it affect the speed of the water? If yes, then is it disadvantageous?". The answer is yes. The turbines will slightly slow down the speed of the water. However, in this case, it is advantageous, as the water will now flow slower and condense the steam more effectively, increasing efficiency. There are also multiple ways to make the turbines environmentally friendly, hence making this solution even more sustainable.

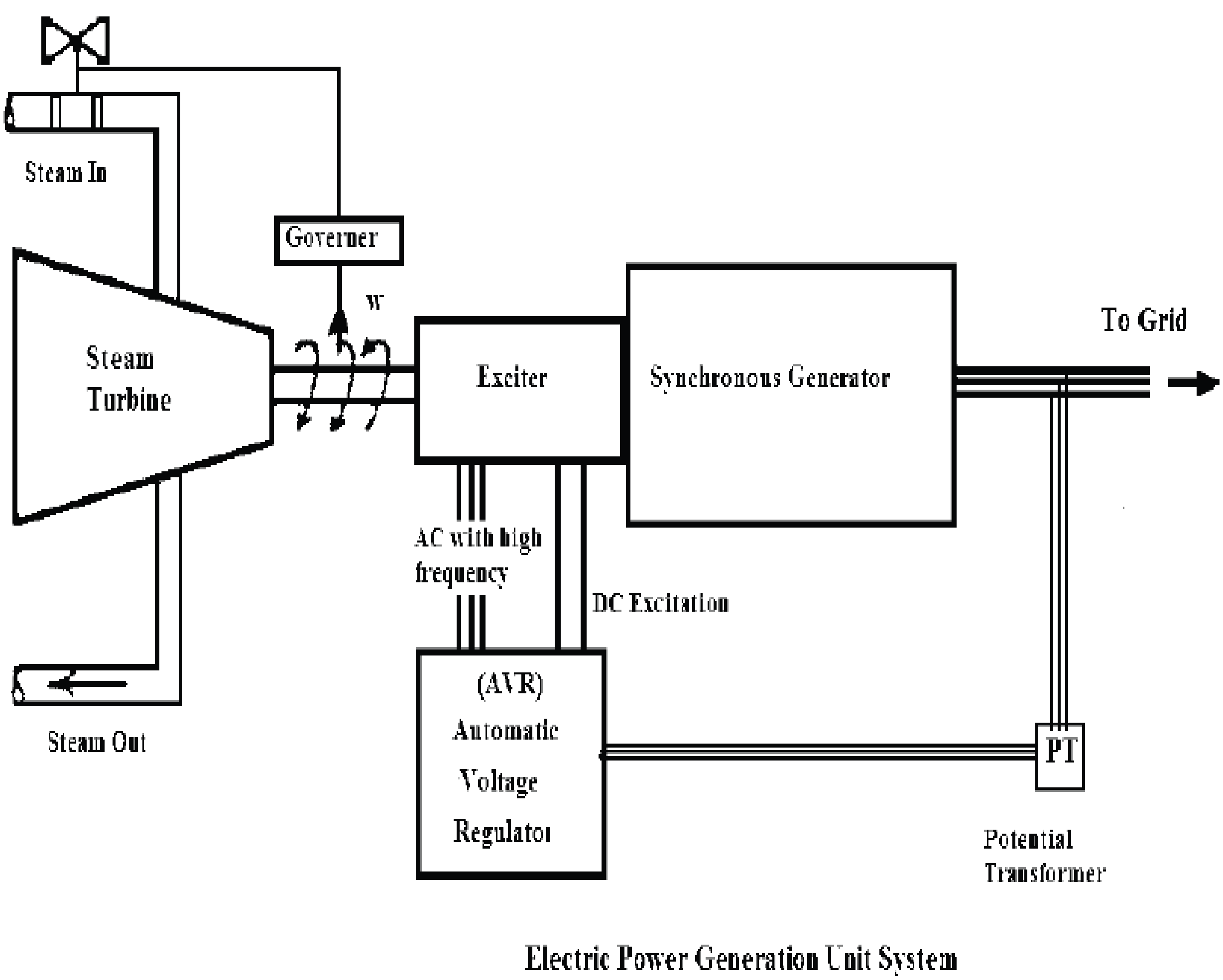


Figure 6: Block diagram of the Electric Power Generation Unit System
Source: Zribi (2013)

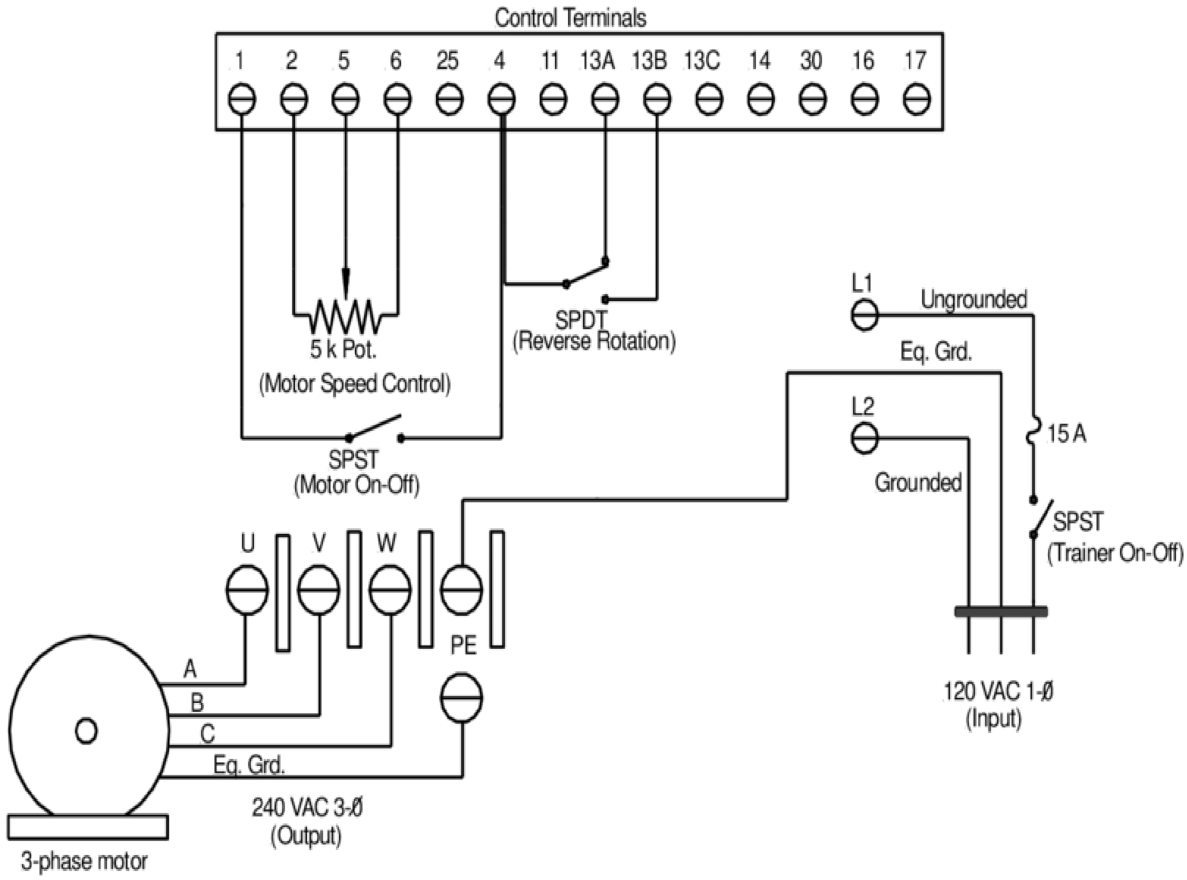


Figure 7: VFD wiring diagram showing power in, power out, and control device connections Source: Johnson (2021)

Potential Challenges

Even though this looks like a good solution, it can result in various problems such as leakage and blockage of the pipe, along with corrosion of the turbine and introduction of impurities in the water. This will lead to increased maintenance and safety measures. At times, most of these pipes may be inaccessible for maintenance and hence need to be rearranged for better accessibility.

Safety measures to be taken

1) Proper insulation of the turbine to prevent electric shocks
2) Alloying/galvanization or other measures to reduce corrosion in pipes and turbines
3) The turbine must be of appropriate quality and power
4) Insulation of electric cables
5) Proper arrangement of turbines to ensure laminar flow
6) Regular monitoring of impurities that may enter the water
7) Regular maintenance of piezoelectric sensors and other electrical and mechanical equipment

Maintenance

1) Regular maintenance is required to look into the functioning of the valves at the junction of the pipes
2) Maintenance of pipes and regular replacement/repairs to be done to avoid corrosion
3) Regular removal of waste and sediments to be done
4) For maintenance work, sensors can be fitted in and around the pipes that detect sedimentation, corrosion, wear and tear in the pipes and generators. These can then be connected via IoT (Internet of Things), hence providing easy access.

Approximate Revenue Generation
(Done by the author using Omni Calculator – Hydroelectric Power Calculator)

Turbine type	"Run-of-river" installation
Cross-sectional area	0.16 m^2
Flow velocity	12 m/s
Flow discharge	1.92 m^3/s

Expected output power	
Efficiency	59.3 %
Power output	81.81 kW

Revenue	
Operating days	365 /year
Tariff	0.16 د.إ/kWh
Revenue	114,668.21 د.إ/yr

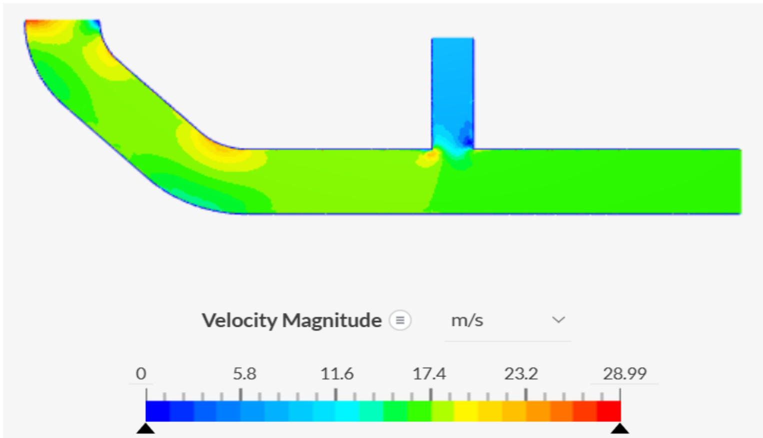
After entering the approximate cross-sectional area, velocity, and efficiency, the results are as given - the estimated revenue generated by just 2-3 of these pipes is approximately USD 115,000. This can, in turn, reduce electricity rates and make electricity more accessible, cost-effective, and sustainable. This revenue can easily cancel out all maintenance and implementation costs.

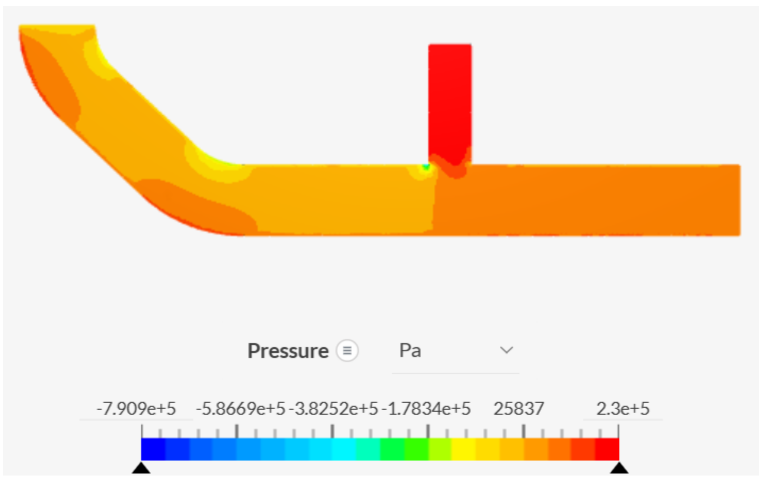
Determining the best position to install the turbine using computational fluid dynamics
(Done by the author using SimScale simulation)
After entering the approximate values for pressure, velocity, area, volume, temperature and boundary conditions, the results obtained are:

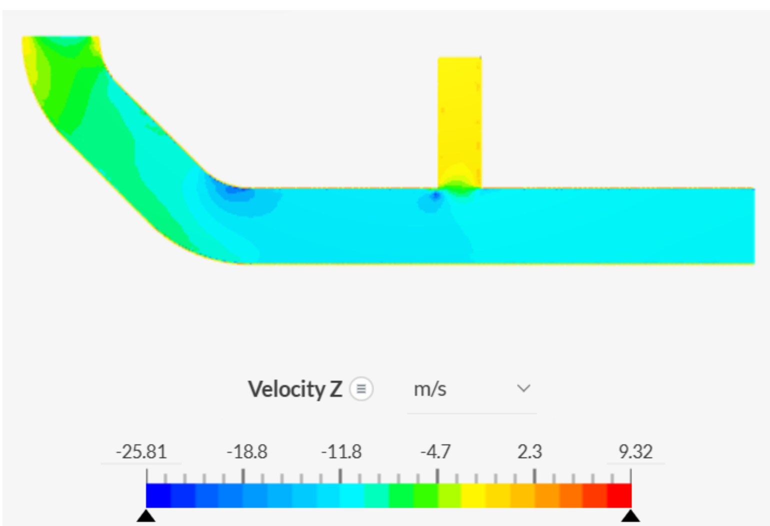
Velocity Analysis:
Flowing fluid: Water
Gauge pressure: 2 bar
Velocity:

U_x = 0 m/s
U_y = 0 m/s
U_z = -25 m/s (entering), -15 (exiting)
Turb. Kinetic energy: 0.00375 m^2/s^2
Specific dissipation rate: 3.375 1/s
Boundary conditions: Velocity inlet 1, velocity inlet 2, pressure outlet

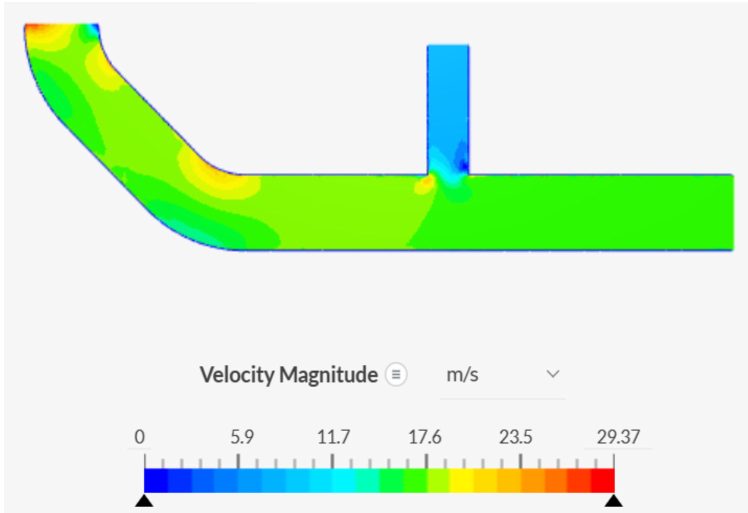
Coolant Exiting Phase

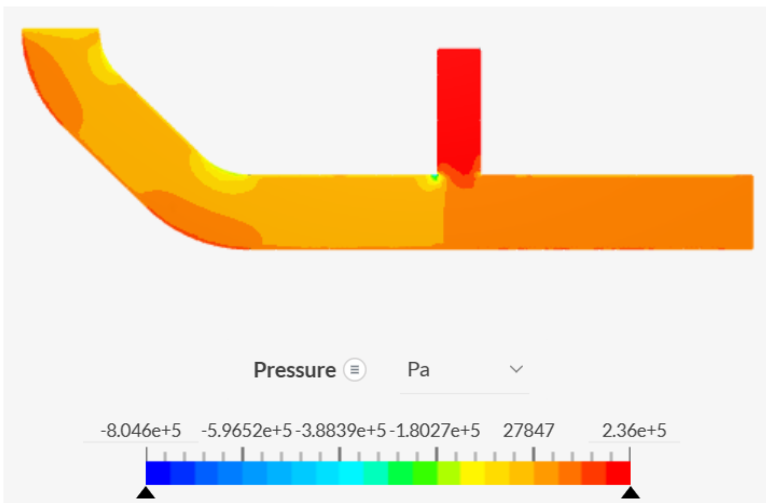


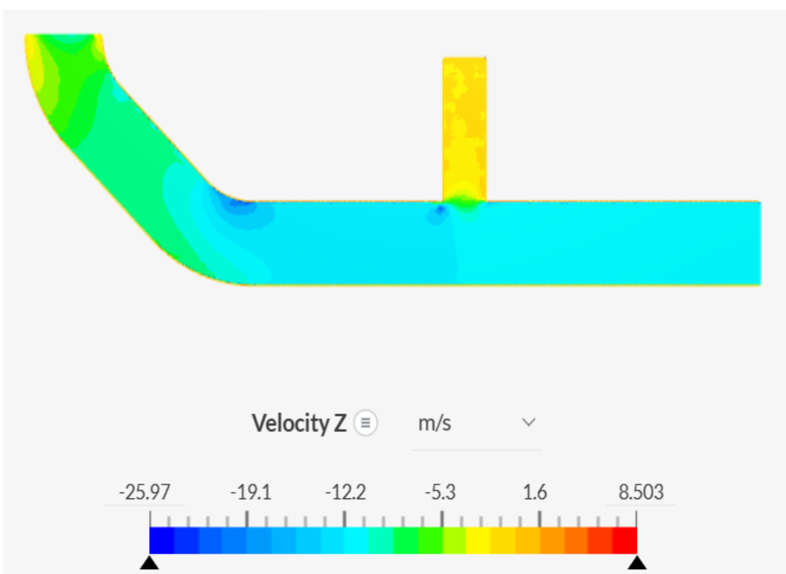




Coolant entering phase

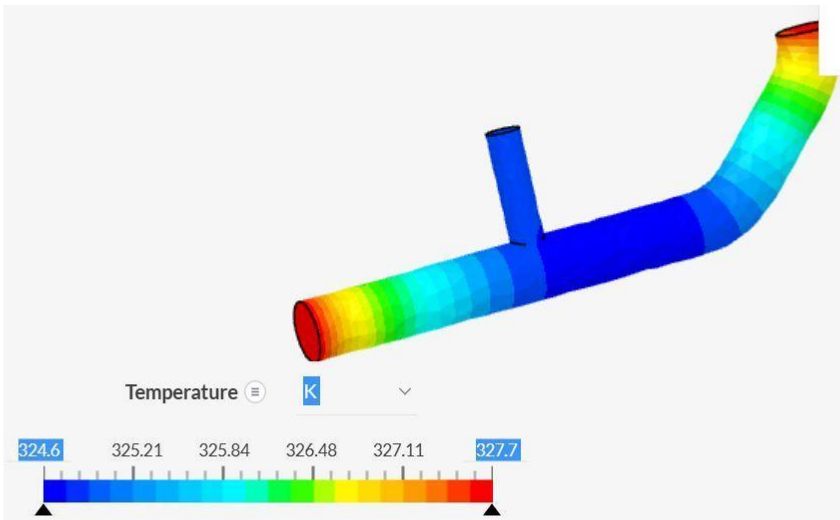




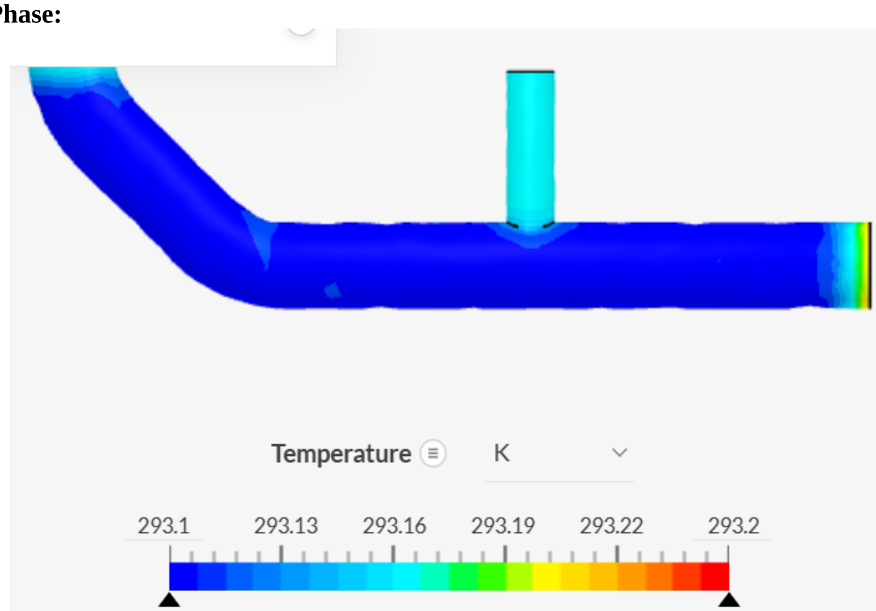


Heat Analysis:
Material: Steel
Temperature: 20 degrees Celsius (entering), 50 degrees Celsius (exiting)
Boundary conditions:
Surface heat flux 1: 150 W/m^2
Convective heat flux 2: Reference temperature – 15 degrees Celsius, heat transfer coefficient: 10 W/Km^2
Surface heat flux 3: 150 W/m^2

Coolant Exiting Phase:



Coolant Entering Phase:



After a thorough analysis, the preferred position of the turbine appears to be in the middle of the pipe, right before an alteration in the trajectory of the fluid. This is due to the relatively low temperatures and high pressures and velocities in these areas.

Similar innovation

1. According to Emiliano Bellini (2023), another innovation by Japan's Ricoh consists of a micro hydropower system for sewage plants that could potentially be used in combination with ground-mounted solar or floating PV,

along with an environmentally sustainable turbine design. The imaging and electronics company said that the electricity generated by the micro-hydro system could be used to power sewage plants.

Ricoh provided its 3D printer technology to create the 3D-printed blades used in the system. These are made of biomass-derived materials.

"Compared to a water turbine made from commonly used 3D printer materials, our turbine is more than twice as strong as a metal turbine. Its strength was maintained even after being placed underwater for a long period of time and could be used for large-scale hydroelectric power generation." – Spokesperson, Ricoh, Japan

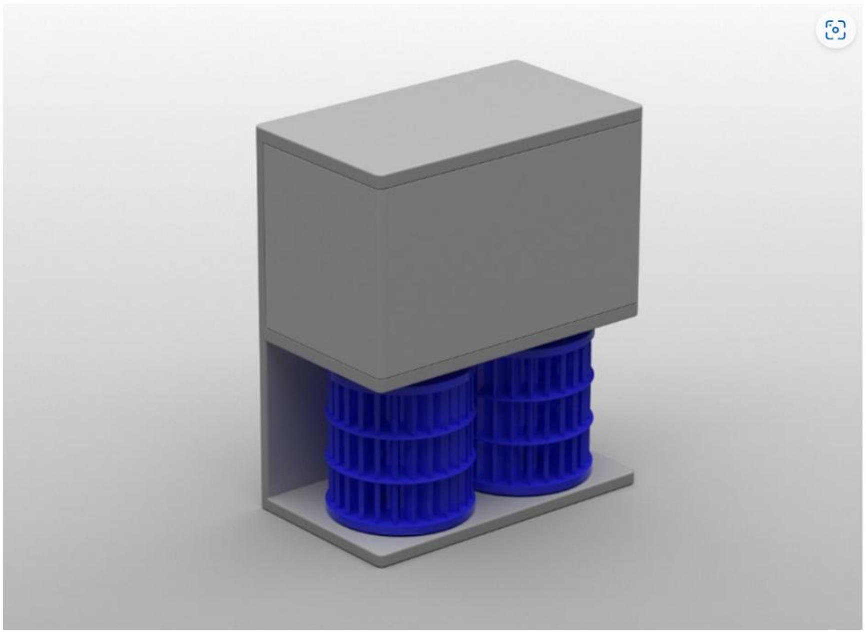


Figure 8: Japan's Micro electric Power System
Source: Ricoh (2023)

2. In Pipe Energy is a Portland-based renewable energy company. The company's flagship product, the In-PRV, generates low-cost, carbon-free electricity from the flow of water in pressurized pipelines. This is done by fitting turbines in pipelines that carry water to our homes, hence generating electricity from an essential water current.

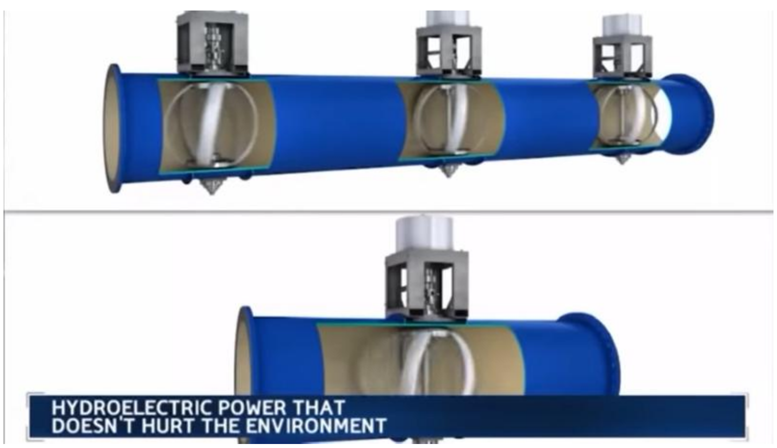


Figure 9: Hydroelectric power generation system of InPipe Energy
Source: YouTube (2013)

Since these innovations is very similar to the one in the power plant and are proven to be effective and safe, it indicates the possibility of my solution being applicable and reliable.

Innovation 2: Utilizing Steam from the Cooling Towers

Introduction: How do cooling towers work?
Water is pumped from a water body into the cooling tower basin. This water circulates through the plant's condenser tubes, absorbing heat from the steam and returning to the cooling tower. Water is then sprayed through the hollow core of the cooling tower and onto the grate in the center of the cooling tower. Cold air flows up from the hollow center, passes through the warm falling water, and part of it evaporates. Evaporation takes heat from the water and cools it. The water in the cooling tower never comes into contact with the water in the reactor, which is a closed system. To complete the cycle, pipes bring the water back into the water body within a degree or two of the lake's normal temperature. This ensures that aquatic life remains unharmed (Michele Burton, 2021).

However, this isn't the case for all nuclear power plants. While large-scale ones use cooling towers, many small-scale plants do not. For such power plants, In the second stream, cooling water travels from a natural reservoir to cool process water in the condenser. According to Brandon Clark (2019), it then travels to a cooling tower, back into the reservoir, or both. Process water is reused in the generation process, but the cooling water is discharged back into a lake, river, or ocean, at a temperature typically around 30-40°C.

During this cycle, 2% of the water that is used in the cooling of condenser tubes gets evaporated in the form of water vapor, i.e., what we commonly see at cooling towers. The rest 98% is simply recirculated throughout the full cycle. However, to replace this 2% water, additional water is drawn from a reservoir, which may lead to gradual water scarcity.

Figure 10: Alert system for failing nuclear plant pipes uses thin films and sound vibrations
Source: Coyle (2019)

Cycle 1
This cycle consists of generating additional electricity from the excess steam released from cooling towers. As the steam can flow easily, a system of fans, compressors, and pumps is required to safely direct the steam to the turbine. This direction can be done by numerous pumps that will push the steam forward. Along with this, there will also be a system of valves and sensors that can be connected to an IoT. This can monitor the flow of steam, raise an alarm in case of an emergency, or even automatically operate the valves. Once at the turbine, there will be present, a high-power compressor and a pump to increase the pressure of the steam as per the energy requirement. This high-pressure steam will then drive the turbine, hence generating electricity. This steam can then be cooled down again, either by reusing exhaust steam or drawing

water in from a reservoir to cool and condense it. Once some amount of steam is unwanted, it can easily be removed by an exhaust system. Even though this solution will release water vapor into the environment, it will still be in lower quantities, whilst generating more electricity. However, we have to note that the main turbine and this turbine have to be different.

Cycle 2

This cycle consists of using extra steam as the coolant for condensers. In fact, this is already being implemented in many places, including some power plants, and even some ships such as the RMS Titanic. To do this, we will have to first condense and cool down the steam. For this, we initially require pumps, fans, and compressors to direct the flow of steam. The steam will then reach another condenser, which uses only fans to cool the liquid down. This will ensure that there is no more water or complex HVAC systems required. Additionally, to make sure that the steam does not simply flow away, it will be supplied through pipes everywhere, even in the condenser. Next, it will go to a heat exchanger, where any excess heat will get dissipated into the atmosphere. At this stage, the steam is low-pressure, cool liquid water, which can serve as an excellent coolant for normal steam or the supplementary steam which was mentioned above. Any excess steam will be dissipated to the atmosphere as mentioned above.

Cycle 3

This cycle consists of directly using the steam for other purposes in the power plant such as temperature regulation, etc. For this, the steam will be directed to the places where it needs to be used, by pumps, compressors, and fans. This movement will also be controlled by valves and regulated by sensors that will be connected to IoT. Once utilized, the steam can be sent to a boiler room or a condenser, depending on the purpose. As mentioned earlier, unwanted steam can also be released into the atmosphere by an exhaust system.

Advantages

1) This solution is very versatile, as it can be used in any nuclear power plant, regardless of size.
2) This solution can be used for a variety of purposes.
3) It leads to cost savings, higher electricity production, and increased sustainability.
4) There is a lot of scope to implement numerous safety measures in such an arrangement.

Potential Challenges

1) Due to the higher number of pipelines, the chances for leakage and accidents increase
2) There has to be regular supervision and maintenance of turbines and pipes to avoid corrosion.
3) To implement all these cycles in one plant, the design will get very complicated.
4) Power plants might have to increase their size to accommodate this solution.

Safety Measures & Maintenance

1) Regular maintenance of the pipes and turbine, along with other machinery is crucial.
2) Proper measures to be taken to avoid corrosion of machinery
3) There also has to be regular supervision of IoT sensors and the electrical circuits to avoid malfunctioning of any equipment.

How can the pipes be properly supervised?

To understand this, an example of Vanderbilt University engineers working on an early warning system would be considered. They use a polymer coating on the inside of the tube and a 3D-printed polymer device filled with nanoparticles as a sensor to signal changes on the outside of the tube. To develop a useful and proactive technique, the team hopes to use acoustic or vibration measurements to identify these internal changes from the outside of the tube. *"The film can chelate metal ions in solution and from corroding surfaces. The chelated metal changes the properties of the polymer film and effectively cross-links the polymer chains,"* said the department head. The coating changes from green to blue with a change in input that could signal a corrosion process. A similar process can be used to supervise the pipes (Coyle, 2019).

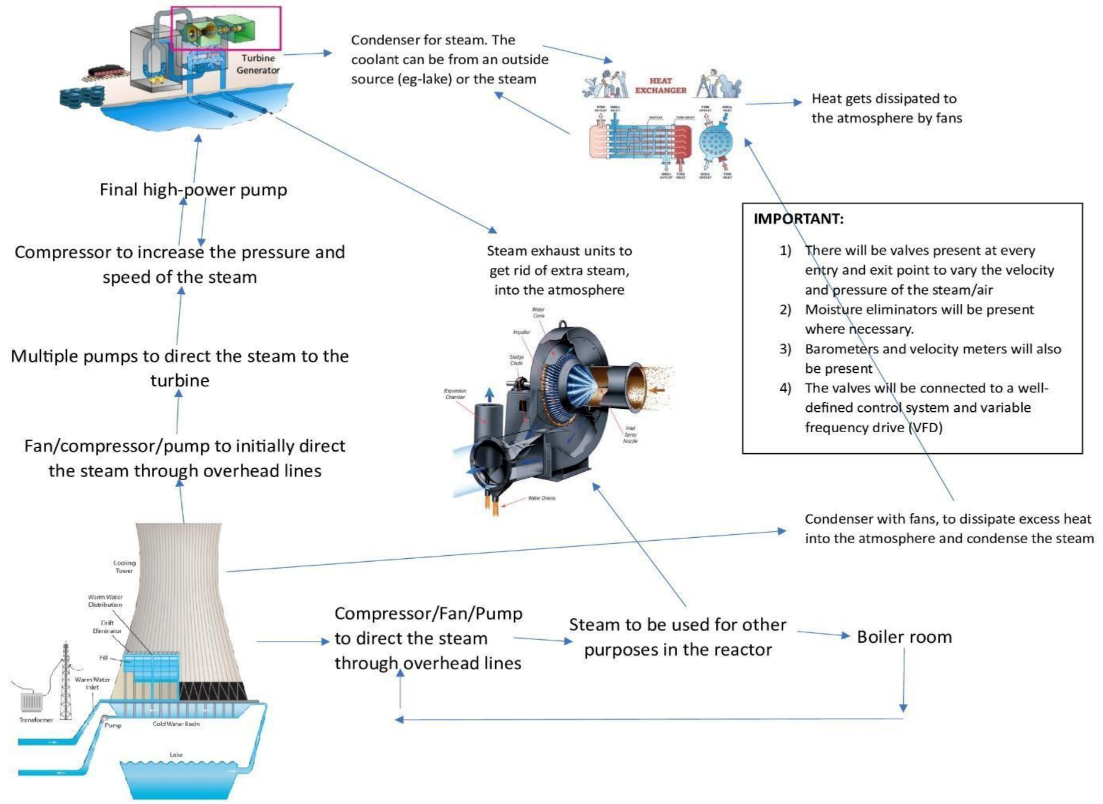


Figure 11: Flowchart describing the working of different steam reusing cycles
Source: Deshpande (2023)

Similar innovation

"Saving Energy through Reuse of Factory Exhaust Heat" – by Fuji Electric (2015)

Reusing Heat Energy through Steam-Generation Heat Pumps

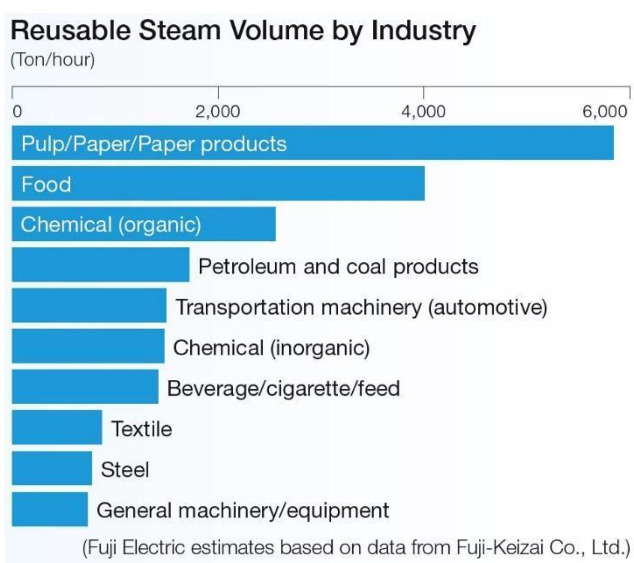


Figure 12: Reusable Steam Volume by Industry
Source: Fuji Electric (2015)

According to Fuji Electric (2015), in factories, a lot of heat is consumed during the manufacturing process, especially in cleaning and sterilizing equipment. Heat pumps that generate steam can collect the waste heat from such equipment and reheat it so that it can be reused. Since the high-temperature reheating load of the boiler equipment is reduced, it is possible to reduce fuel costs and save energy in the factory.

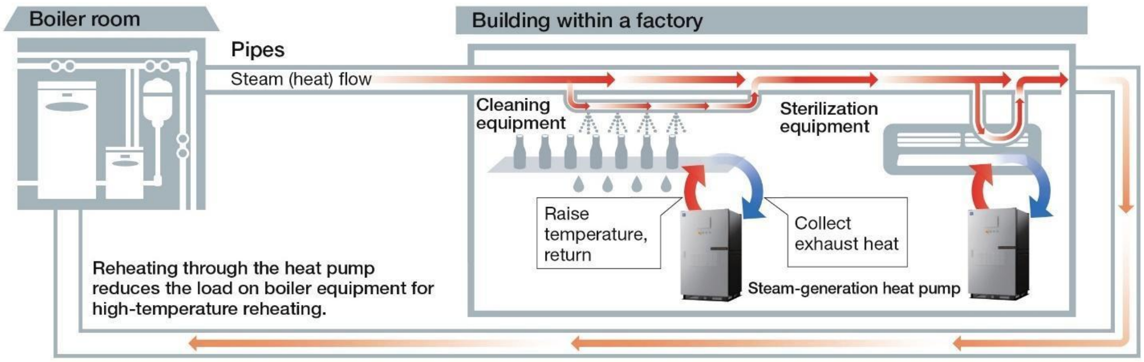


Figure 13: Schematic Diagram of Heat Reusing System at Fuji Electric
Source: Fuji Electric (2015)

What is a "heat pump?"
According to Fuji Electric (2015), because the equipment pumps heat from a “cold side” to a “hot side,” similar to a system used for pumping water, it is known as a “heat pump.” In vending machines, the heat absorbed in the cold compartment where beverages are chilled is condensed in a compressor, and the heat generated in this process is then used to heat beverages in a hot compartment. This greatly reduces the amount of energy used for heating and contributes to energy saving.

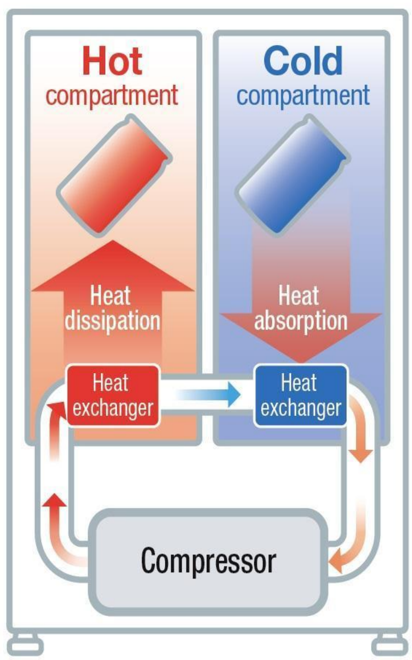


Figure 14: Schematic Diagram of a Heat Exchanger
Source: Fuji Electric (2015)

Case Example - Iiyama Factory, Fuji Electric Power Semiconductor Co., Ltd.

Innovation: Saving Energy by Utilizing Surplus Heat from Diesel Engines
Result: Energy Use Reduced by More Than Half

According to Fuji Electric (2015), Fuji Electric Power Semiconductor Co., Ltd'sIiyama Factory Production is a base for power semiconductors used in automobiles. To ensure a stable power supply for their 24/7 factory, the factory uses diesel engine generators to generate electricity on-site. The waste heat generated by this engine is reused for heating, ventilation, and air conditioning in the factory, but approximately 50% of all waste heat was wasted.

Fuji Electric focused on the steam supplied to clean rooms in factories. Power semiconductors are precision parts, and static electricity generated and discharged during the manufacturing process may adversely affect quality. To prevent this, especially in winter when the air is dry, steam is generated and sent to the clean room with a separate boiler. In March 2015, Fuji Electric's Mie Factory began demonstrating a steam-generating heat pump that it developed to generate steam for clean rooms using exhaust heat from diesel engines, with the aim of further saving energy.

The steam generation heat pump itself is about the size of a typical vending machine. It is easy to use, requires no special construction, and can be installed in just a few hours. After installation, energy consumption in was reduced by approximately 55% and CO2 emissions by approximately 40% compared to before installation. Boiler usage had also decreased.

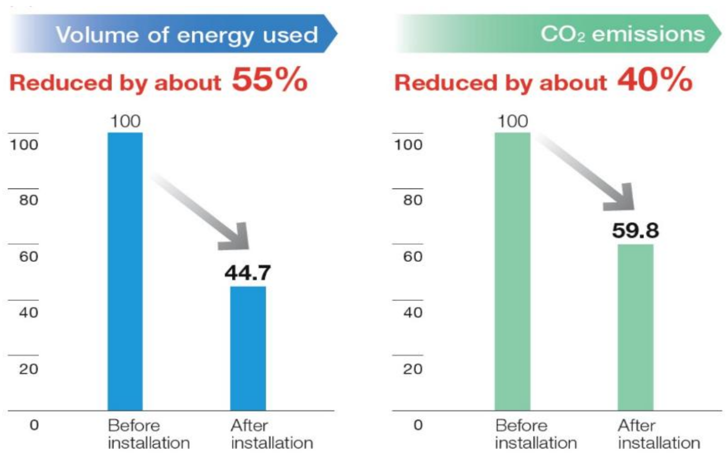


Figure 15: Post-deployment results
Source: Fuji Electric (2015)

Figure 16: Steam Generation Heat Pump
Source: Fuji Electric (2015)

Figure 17: Power Semiconductor post-process
Source: Fuji Electric (2015)

CONCLUSION

As the energy industry is constantly evolving, the scope for innovations to increase efficiency is highly present. This research paper is yet another contribution to innovations in the nuclear energy industry. After a thorough analysis of existing solutions and the behavior of high-temperature fluids in pipelines, a promising solution of fitting generators in pipelines, and reusing exhaust heat was proposed. Moreover, the solution is also proved to be highly economical and sustainable with the help of a series of experiments and similar innovations. The paper also highlights existing innovations and how several of the same can be incorporated into the energy generation sector. Lastly, there is always scope for further research on material science and engineering to develop sustainable and efficient methods to reuse the heat and radioactivity of spent nuclear fuel, and various recycling opportunities for spent nuclear fuel.

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