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Numerical analysis of nuclear reactor passive safety cooling driven by natural air circulation in a Small-scale Novel Vortex Tower coupled with nuclear power plant

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Abstract

The natural circulation (NC) flow is a significant process in many industrial systems, and understanding its behaviour is vital for nuclear reactor design, operation and safety [1]. The primary goal of this work is to model, simulate, and analyse the kinematic, dynamic, and thermal aspects of natural airflow circulation using a Small-scale Novel Vortex Tower (SNVT-1/5) model carried out in our institution (CRNB). This work is part of a project to analyse and develop a vortex tower prototype based on airflow heated by a nuclear reactor's secondary circuit, see in Fig 2. [2, 3]. This device employs an artificially formed vortex and is installed on an open area with elevated concrete apertures to maintain general stability, allowing air to penetrate via the intake openings that pass across the hot source and moves upward along the chimney during heat convection, see Fig. 3. The thermal energy of the heated air from a natural hot source is transferred to kinetic energy due to the density difference effect, which is converted into mechanical energy via turbines and transferred into electrical power.

The nuclear power plant cooling system and the realized SNVT are linked, which greatly minimizes the quantity of cooling water utilized from rivers or the sea. An overview of the suggested design, which explains how to establish this coupling, is provided in Fig. 2. The bulk of the hot water departing the condenser initially runs via the SNVT, which releases some of its heat to the air, and the remainder returns to the traditional cooling tower, which only requires a little quantity of water to remove its heat.

Introduction

To install a nuclear power plant in an area or zone where the availability of water poses a serious problem, through this study we propose a technical solution to minimize the consumption of cooling water and extract part of energy comes from the condenser and return to classical cooling tower (BWR or PWR) on which we use a small amount of supply cooling water. We propose through this study, to couple a classic cooling tower a new configuration of vortex cooling tower using natural phenomena such as vortex effect, chimney effect and curiolis effect for the natural circulation of air as coolant for this device. This new installation improves the performance of nuclear power plants, saves part of water resources , minimize its loss and reduces thermal pollution.

System description

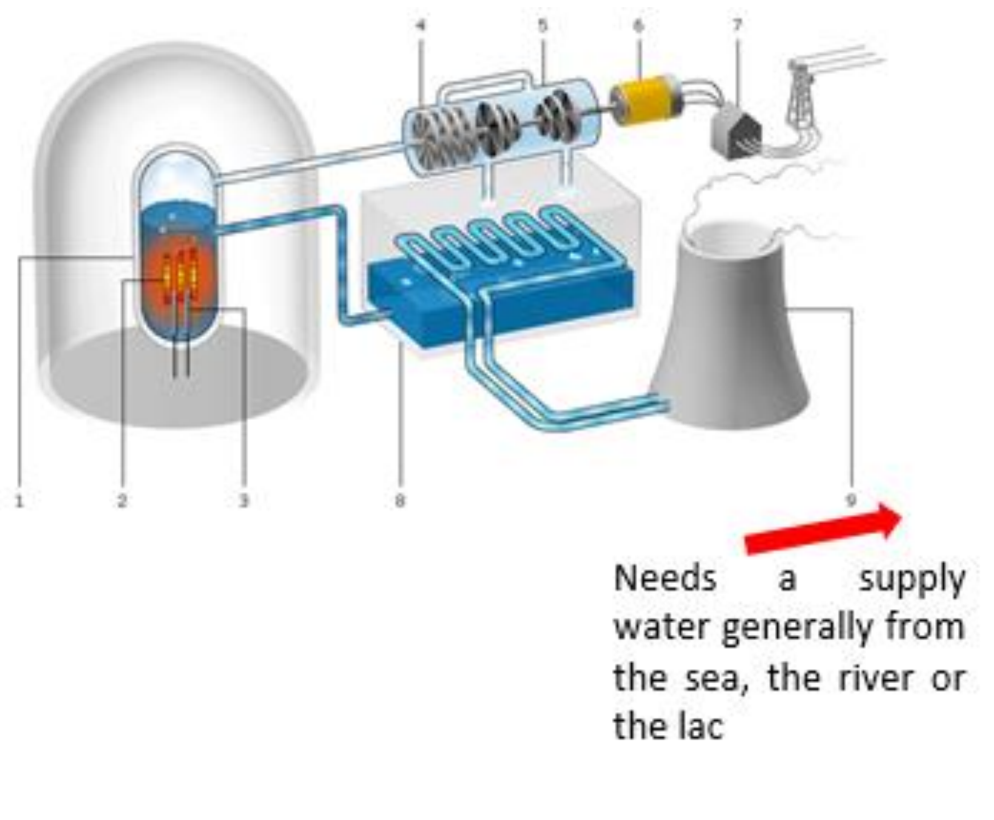

FIG. 1 Classic connection of the tower to the reactor condensation circuit [2]

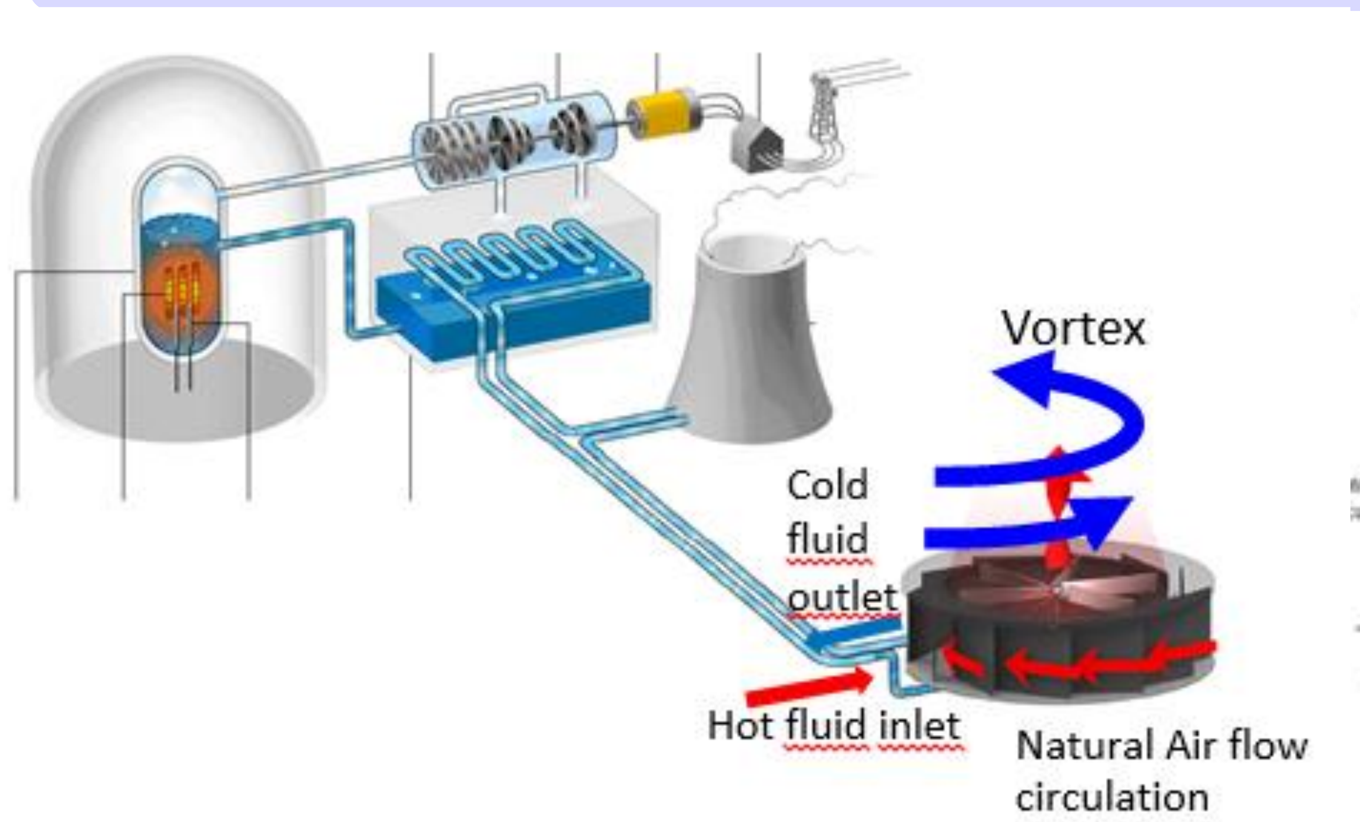

FIG. 2 New connection design from reactor condensation to Vortex Tower then the classical tower [2]

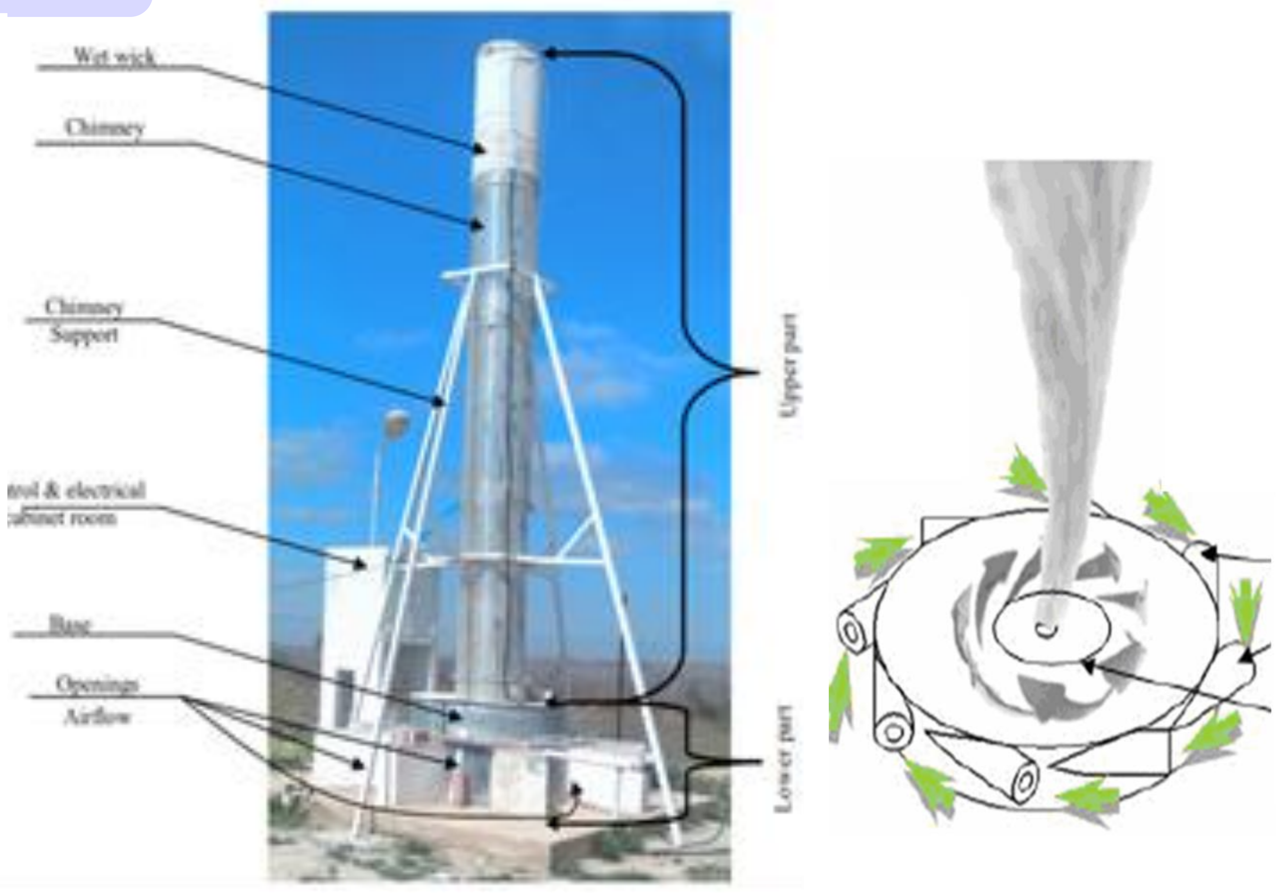

FIG. 3 Prototype of a Small-Scale Novel Vortex Tower (SNVT) [2], [3]

Methodology

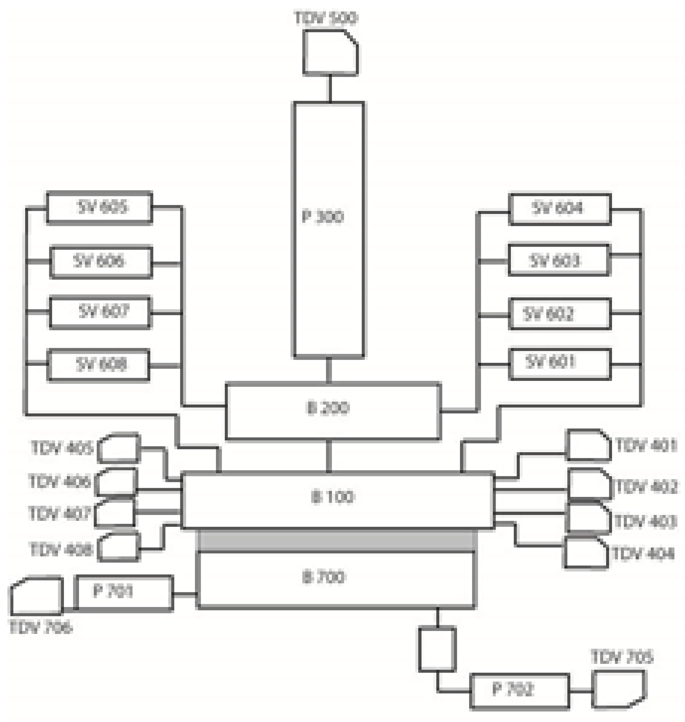

FIG. 4 RELAP5 nodalization diagram of the Small-scale Novel Vortex Tower SNVT

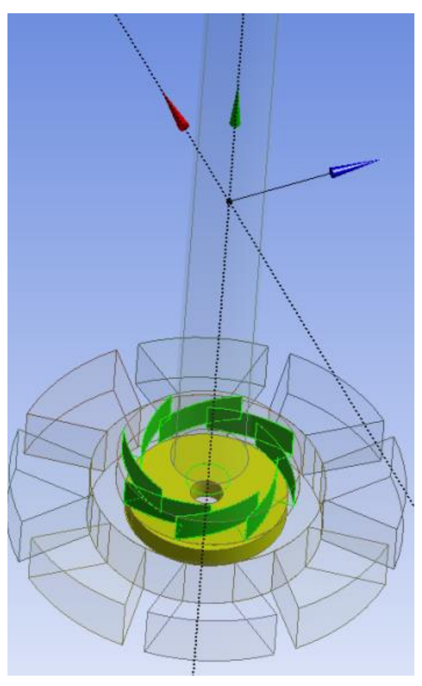

FIG. 5 ANSYS-CFX Geom model of the SNVT [2]

By solving the energy balance equations for heat transfer from the hot fluid to the tank structure and from the tank structure to the environment, along with the equation for the conversion of kinetic energy of the hot air into electrical energy through the dynamo in the case of reduce scale in the laboratory, this is our case study, and by turbine on the real scale, we can determine the overal energy balance and the efficiency of energy conversion in the Vortex Tower Prototype. This process is supported by RELAP5 and ANSYS-CFX codes.

The energy balance equation can be written as:

$E_{in}=E_{out}$

The total energy at the system's inlet (E_{in}):

$E_{in}=E_{thermal}+E_{kinetic} =m,C_p,T_{in}+(1/2).m.(v_{in})^2$

The total energy output E_{out}:

$E_{out}=E_{tank}+E_{environment}+E_{electric}$

$E_{out}=Q_{tank}.t+Q_{environment}.t+P_{electric}.t$

Q_{tank} ,$Q_{environment}$: the rate of heat transfer

$P_{electric}$:the power output of the turbine or dynamo

Results and analysis

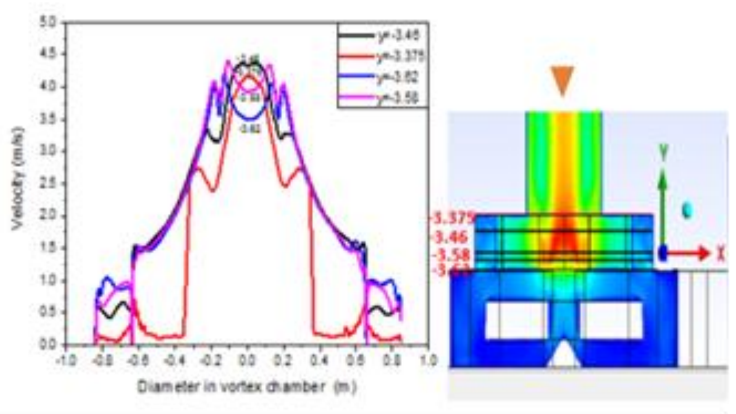

FIG. 6 CFX Velocity contour and magnitude at different position in the vortex chamber [2]

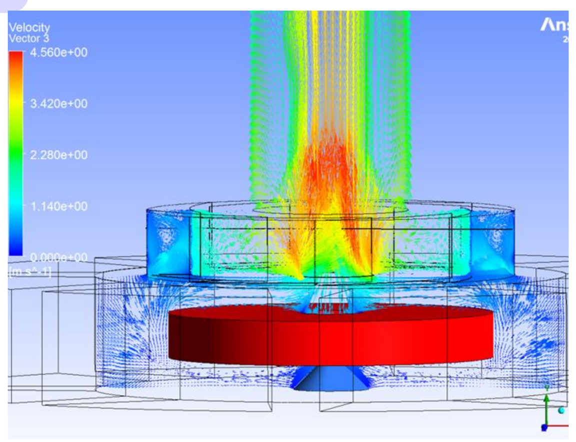

FIG. 7 CFX velocity vector of the flow air in the vortex tower for CFX calculation.

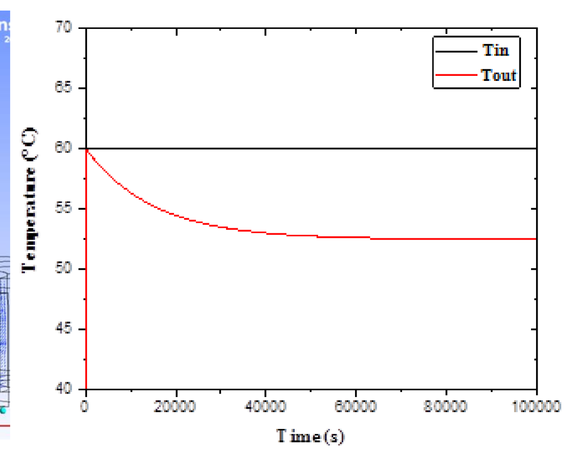

FIG. 8 RELAP5 Temperatur inlet and outlet through the hot source tank.

FIG . 9 Behavior of the fumes at the exit of the vortex tower chimney.

The peak air velocity up to 4.35 m/s is found in the chamber vortex near the chimney entrance, see FIG 6, with a ratio of 43 times over the inlet velocity.

The air temperature near the hot tank rises and the temperature gradient is significant, this means that the naturally circulating air remove heat from the hot source to the air, see FIG 10. The temperature difference between the inlet and the outlet of the tank is estimated to 7,5 °C, see FIG 8.

The theoretical power produced at the maximum velocity was 101,21 Watt.

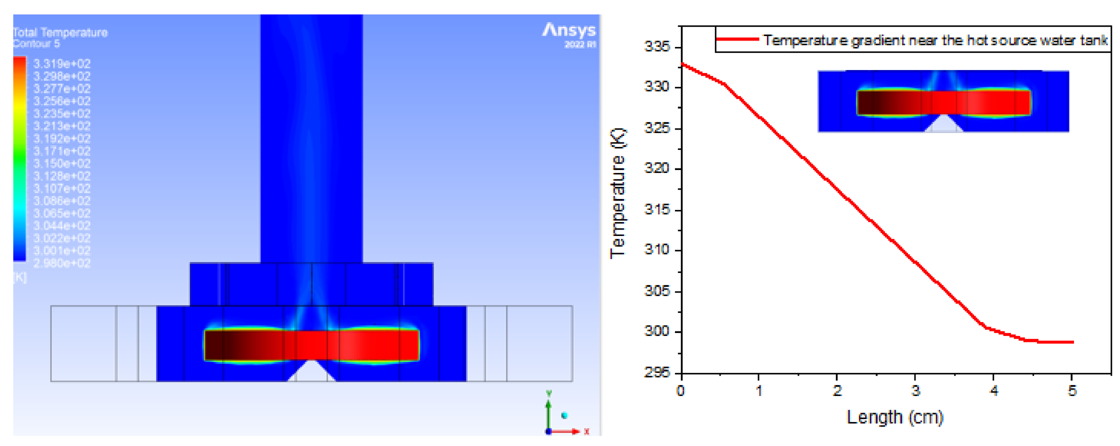

FIG. 10 Temperature contour and gradient variation near the hot source water tank

Conclusion

The analysis of the airflow and heat transfer through a Small-scale Novel Vortex Tower SNVT using Relap5 and CFX codes has been presented. The SNVT is a successful system for producing electricity and extracting a portion of the energy from the secondary circuit of a nuclear power plant with conservation of part of the cooling water. The results analysis showed that this vortex tower is able to generate an airflow peak air velocity up to 4.35 m/s found in the chamber vortex near the chimney entrance with a ratio of 43 times over the inlet velocity and a $\Delta T_{water(In-Out)}$=7,5 °C which contributes to a theoretical power of 101,21 Watt at the maximum velocity.

References

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3. Cheridi, A.D., et al., *Numerical investigation of a novel cooling vortex tower using Relap5 computer code*. Nuclear Engineering and Design, 2022. **391**: p. 111730.