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Investigation on Thermal Hydraulics Characteristics of a Thermosiphon for Efficient Decay Heat Removal

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ABSTRACT

A thermosiphon can be used as a passive safety component, which can be used for the removal of decay heat from the nuclear reactor core. By investigating the characteristics of the fluid flows in a thermosiphon, the heat transfer characteristics of a thermosiphon for decay heat removal can be analyzed. The focus of this study is to simulate and analyze the heat transfer and fluid flow characteristics in terms of an onsite power failure and normal shut-down for maintenance. In this study, a comparison of heat transfer has been shown between an open loop and a closed loop thermosiphon, and a comparison of fluid flow characteristics is determined. The finite element method has been used to conduct the study within 300-400K temperature. Reynolds Number and Nusselt Number are the main dimensionless number to study. High Reynolds and Nusselt numbers have been found in the closed-loop thermosiphon than in the open loop, indicating more efficient heat transfer along closed-loop thermosiphons. The Navier-Stokes equation and the continuity equation, the basis of Computational Fluid Dynamics (CFD), have been used as the principle governing equations to conduct the study. ANSYS has been used to experience numerical investigation. At the beginning of this study, the models of open-loop and closed-loop thermosiphons were created. Proper meshing, boundary condition and initial condition were applied to the model for CFD simulation to get the desired results. The results of the simulation were compared with an experimental result for validation. The study's key findings are that the Reynolds number and Nusselt number of the closed-loop thermosiphon are higher than the open-loop thermosiphon. Thus, faster heat removal of the decay heat from the reactor core can be achieved through the closed-loop thermosiphon.

Keywords: Thermosiphon, Computational Fluid Dynamics (CFD), Navier-Stokes equation, ANSYS, Decay Heat Removal.

1. Introduction

The safety of a nuclear power plant has been a concern over the years for enhancing the nuclear industry [1]. Decay heat removal corresponds to the protection of a nuclear power plant as it appears as one of the fundamental challenges. Decay heat generation is a common phenomenon in nuclear power generation after reactor shut-down or during reactor accident scenarios. In standard power operation, heat is removed from the reactor using several Thermal hydraulics-based components such as the steam generator and pump. After the reactor is shut-down or during an accidental situation, remove the decay heat generated. Usually, there are two types of circuits in a nuclear power plant: Primary and secondary. The Rankin cycle is the most important one, corresponding to the secondary circuit. The decay heat removal process can be accomplished via two methods. The first is the active method which requires electricity to run the necessary active components. The second one is the passive heat removal method which does not require any external power supply and is mainly used during any transient condition to ensure a safe environment inside the reactor. A safe reactor operation is also one of the requirements of defense in depth [2-3].

This simulation is based on the decay heat removal by the natural circulation process in a closed-loop thermosiphon. A CFD simulation calculates the heat transfer through the natural convection of the fluid inside the closed loop by considering the Nusselt Number throughout the system.

A two-dimensional incompressible, viscous and turbulent flow has been considered between the closed loop. The experiment defines the source and sink for the heat transfer from the heat source to the heat sink. The closed-loop walls are considered adiabatic, meaning no heat can enter or exit the coolant into the environment. When heat is applied to the source, the coolant absorbs it, making it less dense than its surrounding coolants. This low-density coolant travels by the riser to the heat sink. In the heat sink, the less dense coolant exhales the absorbed heat and becomes a relatively highly viscous liquid. This relatively highly dense coolant in the sink travels by downcomer to reach the source and absorbs heat, then continues repeating the process for the decay heat removal system. This study aims to investigate the thermosiphon's heat transfer characteristics through the dimensionless number and to co-relate the findings to the decay heat removal in the nuclear reactor core.

2. Theoretical Background

Decay Heat Removal: Decay heat is generated in the reactor core after shutting down or in an accidental period. The heat is dispersed by bypassing the turbine and

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discharging the steam directly into the condenser. When pressure drops below 11.7 MPa inside the reactor, the reactor shut-down auxiliary cooling system initiates, and safety valves open. Thus, Passive Core Cooling System also turns on to execute the core cooling process [4]. Water is circulated via a recirculation loop from the heat exchanger and returned to the reactor core. The recirculation loop is designed to keep penetrations into the reactor vessel minimum.

There are two broad kinds of methods for reducing decay heat from a reactor core:

- **Close-Loop System:** There are two techniques for coursing liquid around the reactor core in a closed circle while getting heat from the system.
    - **Heat Removal through Steam Generators:** Reactor decay heat can be directed by steam generators to the primary condenser or the atmospheric steam dump system. Some reactor coolant pumps (RCPs) must operate continuously in this mode for natural circulation to have been preserved.
    - **Heat Removal through RHR:** The residual heat removal system uses a low-pressure heat removal system (RHR). One or more RCS hot legs are used to pump water and cooled in RHR heat exchangers before being returned by PWRs to the cold legs or core flooding tank nozzles. Heat is transferred from RHR heat exchangers to the component cooling water or service water system, which then transfers the heat to the final heat sink to complete RHR heat removal (UHS).
- **Open-Loop System:** This method releases heated liquid to a storage area or the environment while collecting cool fluid from another source.
    - **The feed-and-bleed method** is utilized to reduce decay heat. In some pressurized water reactors, the feed-and-bleed technique for removing decay heat becomes crucial if the heat sink capability of the steam generator is compromised (PWRs). The feed-and-bleed method removes heated coolant from the primary system via a PORV or pilot-operated relief valve. Subcooled coolant is supplied to the primary system via a high-pressure safety injection system (HPSI), a component of the emergency core cooling system.

Reynolds Number: Within a fluid exposed to relative internal movement due to various fluid velocities, the Reynolds Number is the ratio of inertial forces to viscous forces. When viscous forces dominate (low Re, slow flow), it may be argued that they are sufficient to keep all fluid particles in line; hence, the flow is laminar. When inertial forces outnumber viscous forces, the flow becomes turbulent (when the fluid flows faster and R_e is bigger). Various parameters influence the transition from laminar to turbulent flow, including surface geometry, surface roughness, free-stream velocity, surface temperature, and fluid type.

The Reynolds number is defined as:

$$R_e = \text{Inertia force}/\text{Viscous force} = \rho v D/\mu \qquad (2.1)$$

Here,

V = flow velocity of the fluid
ρ = fluid density (kg/m^3)
μ = dynamic viscosity (Pa. s)
ν = kinematic viscosity (m^2/s); $\nu = \mu / \rho$

Laminar and Turbulent Flow: Laminar flow describes the movement of a fluid in which each particle follows a smooth route that never intersects with another. Streamline, or viscous flow are terms used to describe this flow. The fluid velocity is constant at every location in the liquid in laminar flow. Examples include flow in a capillary tube, water flow in veins and arteries, groundwater flow and others.

The transition from laminar to turbulent depends on the following:

i. Surface geometry
ii. Surface roughness
iii. Upstream velocity
iv. Surface temperature

Nusselt Number: The Nusselt Number (N_u) is the convective to conductive heat transfer ratio over a fluid boundary. Nusselt number is an essential parameter in thermal hydraulic characteristics. Large Nusselt numbers mean effective convection and heat transfers in the shortest time.

Nusselt number is determined by using the following formula:

$$N_u = ((h*d)/k) \qquad (2.2)$$

$$N_u = (q_w*d)/(k*(T_w - T_\infty)) \qquad (2.3)$$

Here,

T_w = Temperature of the wall(k)
T_∞= Temperature of the fluid-free stream or mean temperature (k)
k = Thermal conductivity ($Wm^{-1}k^{-1}$)
h = Convection heat transfer coefficient ($W/(m^2k)$)
d = Distance (m)
q_w= Heat flux per unit area (W/m^2)

Introduction to Thermosiphon: Thermosiphon is a passively operated heat management device that uses natural convection and conduction as its driving forces. The device uses these forces to create a cyclic fluid flow from high to low temperatures and back. Thermosiphon heat exchangers are closed systems that contain an evaporator, a condenser, interconnecting pipes, and an intermediate working fluid (coolant) that can be liquid or vapor. The coil and sealed tube thermosiphons are the two types of thermosiphons employed. The evaporator and condenser of a closed-loop thermosiphon are typically located at opposite ends of the thermosiphon tube with adjacent exhaust and supply ducts. This arrangement is similar to that of a heat pipe system. The evaporator and condenser coils of coil-type thermosiphons are installed separately in the ducts and are linked by short lengths of working fluid pipe. This configuration is evocative of a coil loop system.

In thermosiphon systems, the coolant circulates between the evaporator and the condenser due to a temperature differential and gravity. As a result, thermosiphons can transport heat in either direction equally, one way alone or in both directions unequally.

Cell Zones (Fluid):

- A fluid zone is a collection of cells where all active equations have been solved.
- The input of the fluid substance is necessary (multi-species, phase).
- Source terms can be specified via optional inputs (mass, momentum, energy, and others).
- Fluid zone motion can be defined.

Material Properties:

- The material must be specified for each zone.
- Specific qualities for the material must be specified:
    - Density.
    - Viscosity may be non-Newtonian.
    - Heat capacity.
    - Thermal conductivity.
    - Diffusion coefficients.

Fluid Density:

- For constant density, incompressible flow: ρ=constant
- For compressible flow: $\rho = p_{absolute}/RT$
- Density can also be defined as a function of temperature (Polynomial, Piece-wise polynomial or the Boussinesq approximation model where r is considered constant except for the buoyancy term in the momentum equations) or be defined as the user-specified functions.
- For incompressible flows where density is a function of temperature, one can also use the so-called incompressible-ideal gas law: $\rho = p_{operating}/RT$
- However, for high Mach number flows using coupled solver, set $p_{operating}$ to zero.

3. Governing Equation

Navier-Stocks Equation: The general equation of fluid motion is the Navier-Stocks Equation is based on the conservation of momentum with gravity, pressure and shear forces. The Navier-Stocks Equation is given below-

$$\rho a + \rho g = -\nabla p + \mu \nabla^2 V$$

$$\Rightarrow \rho a = -(\nabla p + \rho g) + \mu \nabla^2 V \qquad (3.1)$$

Here,

'g' is constant,

'a' is Lagrangian acceleration, a function of t, x, y and z.

When $\delta v/\delta t=0$, acceleration is not necessarily zero.

ρa= inertial forces [N/m^3]

$-(\nabla p + \rho g)$ = Pressure gradient (not due to elevation change).

If $-(\nabla p + \rho g) \neq 0$ Then V=0

$\mu \nabla^2 V$ = Shear stress gradient

$T = \mu\,(du/dx)$

Continuity Equation: It claims that the mass flowing through any tube portion in a unit of time is constant for a fluid moving through a tube in a steady flow. The continuity equation is a consequence of the conservation of mass. The amount of fluid entering the pipe from the left must equal the mass of fluid exiting the tube from the right if the flow is constant (velocity, pressure, and density do not change over time).

$$\rho AV = \text{constant}$$

$$\rho A_1 V_1 = \rho A_2 V_2 = \cdots \qquad (3.2)$$

Here,

ρ is the fluid density

A is the area of flow

V is the velocity of flow.

4. Data Collection

Model Information:

Boundary Condition	Pressure Based Solver, Transient
Models	Viscous-Turbulent model
Viscous	Standard k-e, Enhanced wall Fn
Mesh size	0.01m
Material	Copper (Pipe wall), Water (Working fluid)
Closed-loop & Open-loop model dimension	Total length: 362 mm Diameter: 4 mm
Converging criteria	1E-06

Table 1 Data table for closed loop Thermosiphon.

Temp (K)	μ (m^2/s)	ρ (kg/m^3)	V (m/s)	R_e	N_u
373.645	2.9366 E-07	958	0.459	2994769.461	2844.590541
359.589	3.3980 E-07	967.6	0.418	2380557.975	2478.614475
354.953	3.5745 E-07	970.6	0.389	2112538.257	2307.195912
349.575	3.8065 E-07	974	0.352	1801381.847	2096.839519
346.462	3.958 E-07	975.8	0.329	1622224.356	1969.102278
344.576	4.054 E-07	977	0.309	1489358.658	1870.687743
347.66	3.897 E-07	975	0.356	1781370.285	2082.832023
351.418	3.722 E-07	972.8	0.392	2049100.484	2265.372778
355.071	3.570 E-07	970.6	0.419	2278327.171	2414.189617
360.015	3.382 E-07	967.3	0.441	2522645.18	2566.347285

Table 2 Data table for open loop pipe.

Temp (K)	μ (m^2/s)	ρ (kg/m^3)	V (m/s)	R_e	N_u
373.645	2.9366 E-07	958	0.176	1148321.188	1600.441303
372.289	2.975 E-07	959	0.177	1141129.412	1594.419744
367.895	3.1135 E-07	962	0.187	1155574.113	1606.498804
361.575	3.3225 E-07	966.3	0.186616	1085490.088	1547.309675
355.262	3.563 E-07	970.4	0.186245	1014494.235	1485.769621
349.376	3.8156 E-07	974	0.186	949596.3938	1427.989973
344.066	4.08 E-07	977.3	0.186	891067.6471	1374.510714
339.318	4.351 E-07	980	0.186	837876.3503	1324.676047

Data points for closed loop model:

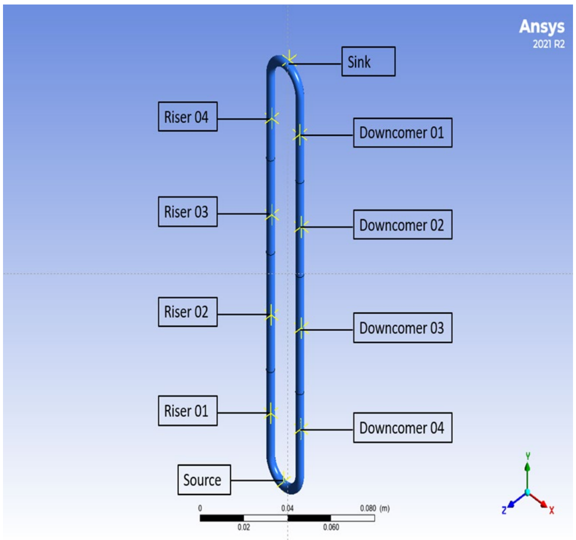

Fig.1: Data collection points of the Closed Loop model

Data points for open loop points:

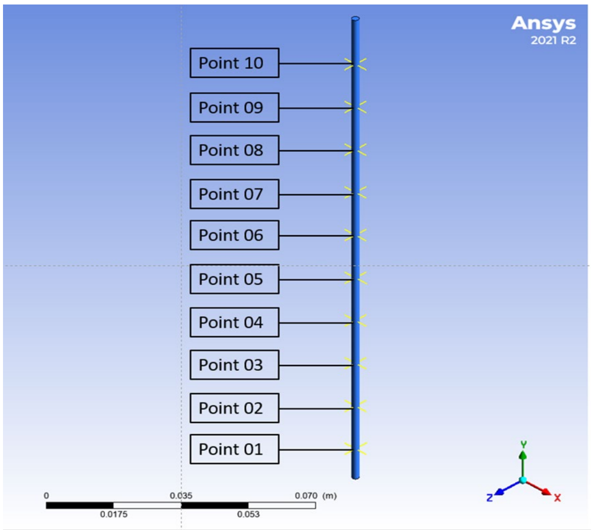

Fig.2: Data collection points of the Open Loop model

5. Results and Discussions

Reynolds number in the close loop: From the following graph (Fig.3), the source point is shown at the right corner of the chart. As the curve gradually approaches the sink, i.e., to the left, there is a gradual decrease in the Reynolds number. It is known that the Reynolds number depends on the bulk temperature of the fluid, and if fluid temperature increases, the Reynolds number increases and vice-versa. That is why the decrease in Reynolds number as the temperature drops from source to sink can be observed. Afterwards, the Reynolds number began to increase as the temperature of the fluid after sink began to rise.

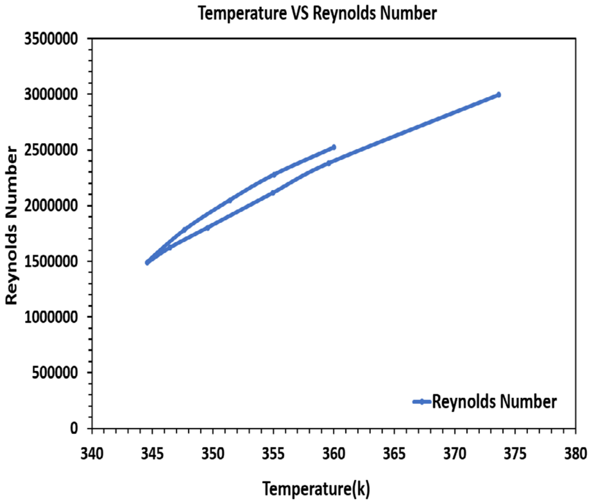

Fig.3: Temperature vs Reynolds Number in closed loop

Reynolds number in the open loop: The right corner of the following graph (Fig.4) has a high Reynolds number as the point is near the inlet temperature. Gradually approaching the pipe outlet, i.e., to the left side of the graph, a gradual decrease in the Reynolds number is seen. Reynolds number depends on the bulk temperature of the fluid, and if fluid temperature increases, Reynolds number increases and vice-versa. Thus a decrease in Reynolds number as the temperature drops from the inlet to the outlet can be observed.

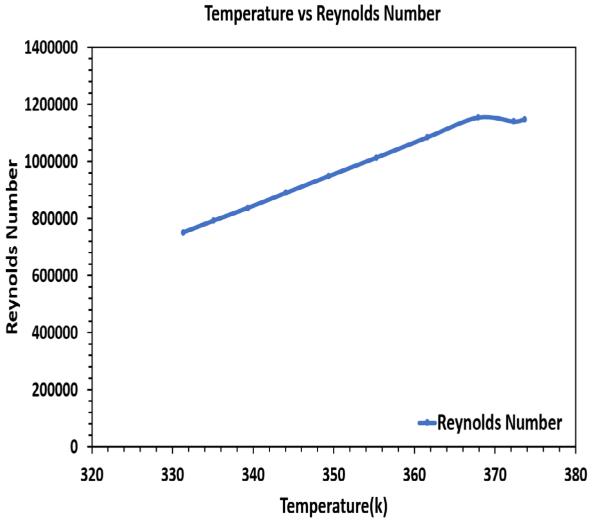

Fig.4: Temperature vs Reynolds Number in Open loop

Nusselt Number in Closed-loop and Open-loop model: The following chart (Fig.5) compares the Nusselt number of closed-loop and open-loop concerning temperature. From the right side of the chart, in the case of the closed-loop, the Nusselt number gradually decreased as temperature decreased from source to sink. Again from the sink to the source Nusselt number increases as the temperature increases.

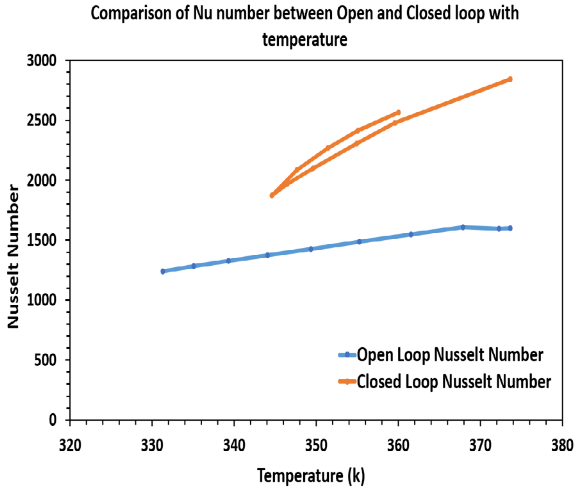

Fig.5: Comparison of Nusselt number between Open and Closed loop model with Temperature.

Temperature vs Time: The following chart (Fig.6) compares the coolant's temperature between the closed and open loops. A change in temperature concerning time characterizes heat transfer. For the closed loop, temperature decreases from the source to the sink point in the chart over time. Again, a rise in temperature after the sink point gradually approaches the source. For an open loop, a consistent temperature drop is observed as the flow moves from inlet to outlet, and the temperature drops more rapidly in the closed loop than in the open loop is shown. However, in the closed loop, the temperature rose after fluid passed through the sink and moved toward the source.

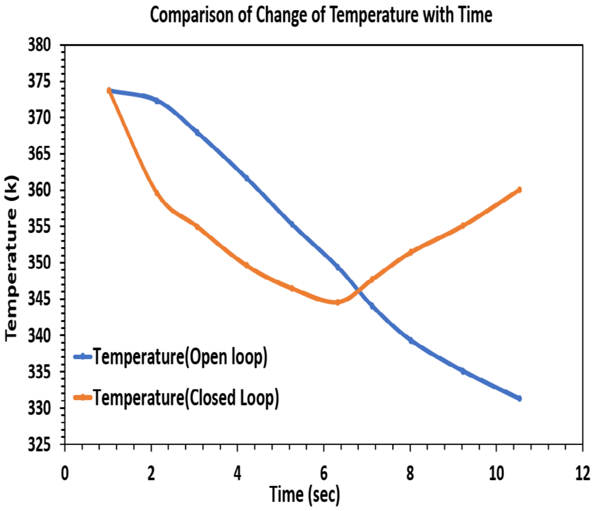

Fig.6: Change of Temperature with Time in Both Closed loop and Open-loop model.

Temperature distribution throughout model length: The following chart (Fig.7) compares the simulation result with the experimental data. The analysis of the temperature of the coolant of a two-phase thermosiphon and the length difference is shown [9].

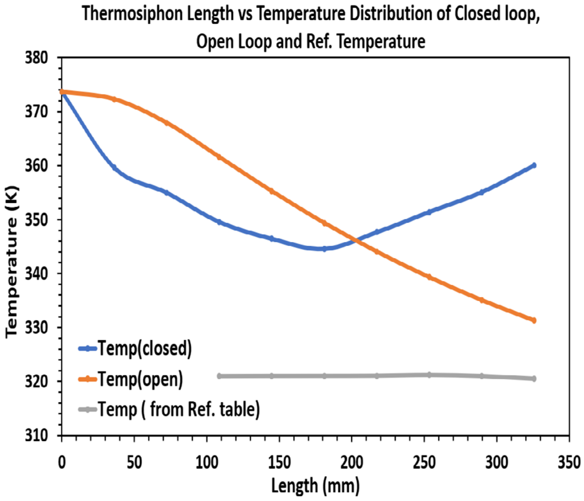

Fig.7: Length vs Temperature distribution of Closed loop model, Open loop model and Ref Temperature.

A normalized plot of thermosiphon, open loop and ref. Temperature: The following chart (Fig.8) shows a common trend between reference and experimental data. The data were compared by normalizing the data table and plotting them. The values from the reference table and the simulation values are normalized to understand their graphical nature better.

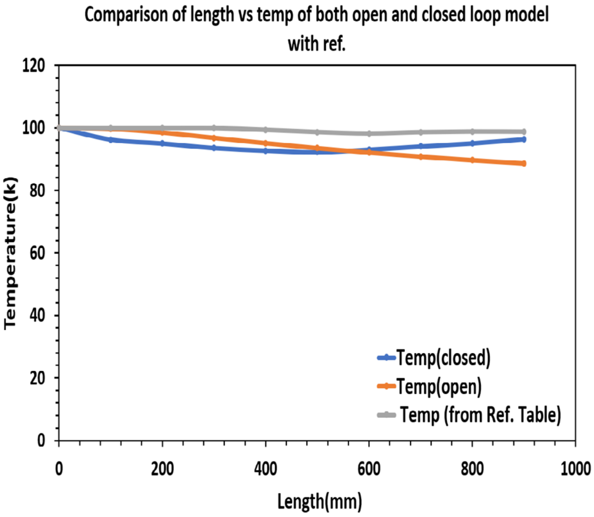

Fig.8: Normalized comparison of Length vs Change of Temperature for Ref. Temp and Thermosiphon.

6. Conclusion

The investigation is accomplished through software modelling and in-depth analysis. The simulation needed to be done with a sufficient run time for acquiring mesh independency. A comparison of the dimensionless number between the open-loop and closed-loop is analyzed in this study. The comparison shows that the closed-loop system has a higher

Reynolds and Nusselt number than the open-loop system. Thus, the closed-loop system has a more efficient heat transfer rate, indicating that efficient heat transfer can be achieved in the nuclear reactor core.

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NOMENCLATURE

c_p : specific heat at constant pressure, $kJ \cdot kg^{-1} \cdot K^{-1}$
F : Helmholtz function, kJ
G : Gibbs function, kJ
h : specific enthalpy, $kJ \cdot kg^{-1}$
p : pressure, kPa
T : temperature, K
t : Celsius temperature, ^{o}C
V : volume, m^3