FEASIBILITY STUDY OF HYBRID HEAT PIPE WITH CONTROL ROD AS PASSIVE IN-CORE COOLING SYSTEM FOR ADVANCED NUCLEAR POWER PLANT

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ABSTRACT

Since Fukushima nuclear power plant accident in 2011, the importance of passive safety has been emphasized during station blackout accidents and associated situation. In conventional emergency core cooling system, refueling water is supplied to the reactor pressure vessel. However, this method had a limitation when pressure inside reactor is too high to inject the refueling water. For passive in-core cooling system (PINCs), the concept of a hybrid heat pipe, which is the combination of a heat pipe and control rod, was proposed for enhanced safety of advanced nuclear reactor. With the unique features of a heat pipe and control rod, the hybrid heat pipe can remove decay heat directly from the core to be inserted into the reactor pressure vessel with the same drive mechanism of a control rod. For demonstrating the feasibility of the hybrid heat pipe, CFD analysis for a single hybrid heat pipe and one-dimensional reactor transient analysis were conducted. Using commercial CFD code, the thermal performance of full-scale hybrid heat pipe was analyzed numerically by solving two-phase flow and heat transfer under high-temperature and high-pressure conditions in reactors. As a result, the hybrid heat pipe concept was found to remove 18.20 kW per rod with total thermal resistance of 0.015 °C/W. From the one-dimensional reactor transient analysis, the hybrid heat pipe was able to delay core heat-up and coolant boiling, assuring sufficient response time at station blackout accidents. If the hybrid heat pipe had 2.5 times improved heat removal capacity, it could continue cooling the core during accidents while preventing core uncovery.

KEYWORDS
Hybrid heat pipe, Heat pipes, Passive IN-core Cooling system (PINCs), CFD

1. INTRODUCTION

On March 2011, a large scale of earthquake of magnitude 9.0 and a tsunami caused severe core damage of the nuclear reactor in Fukushima, Japan. This event showed the vulnerability of the cooling ability of current nuclear power plants during station blackout (SBO) accident and associated conditions. Heat pipe is a totally passive cooling device that is widely used for heat removal of a variety of applications such as electronic devices and CPUs [1].Since heat pipes can cool without external power, their applications have been continuously researched for waste heat management and development of passive cooling systems in field of nuclear energy.

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Singh et al. suggested the heat pipe cooling method as an emergency core cooling system for spent nuclear fuel pool of containment of nuclear power plants [2]. Mochizuki et al. suggested a loop type heat pipe cooling system for a boiling water reactor decay heat removal system [3]. Syiridenko researched a passive emergency core cooling system using heat pipes in Water-Water Energetic Reactor (WWER) [4]. Nam et al. suggested a multi-pod heat pipe cooling system to prevent over-pressurization of containment building [5]. Much research has been conducted on using heat pipes for the development of passive cooling for nuclear power plants. However, the systems developed have to change the existing designs of a nuclear power plant, which can affect the integrity of the facilities. Considering issues that involve the inherent safety of nuclear power plants, the concept of a hybrid heat pipe as passive in-core cooling system (PINCs) was proposed.

Hybrid heat pipe is a totally passive decay heat removal device that combines the control rod and heat pipe as a PINCs. With the unique features of a heat pipe and control rod, hybrid heat pipe is inserted in core to remove decay heat directly from nuclear fuel without any structural changes of existing facilities of nuclear power plants, [6]. Hybrid heat pipes consist of metal cladding, working fluid, the wick structure, and a neutron absorber. Same with working principle of the heat pipe, heat is transported by phase change of working fluid inside metal cask. Figure 1 shows the systematic design of the hybrid heat pipe cooling system. As one of the candidates of heat sink, natural circulation loop with water pool was considered in this study, where removed heat is delivered by the water pool located outside the containment. It can remove heat by convection at first, and temperature of water becomes boiling point at that condition, it evaporates and removes heat with phase change process. Finally, after all water evaporates, heat is removed by air cooling, therefore ultimate heat sink is air. In the design point of the hybrid heat pipe, heat sink loop should be designed to have sufficient capacity at the condenser region to remove all heat transferred from the evaporator section of hybrid heat pipe.

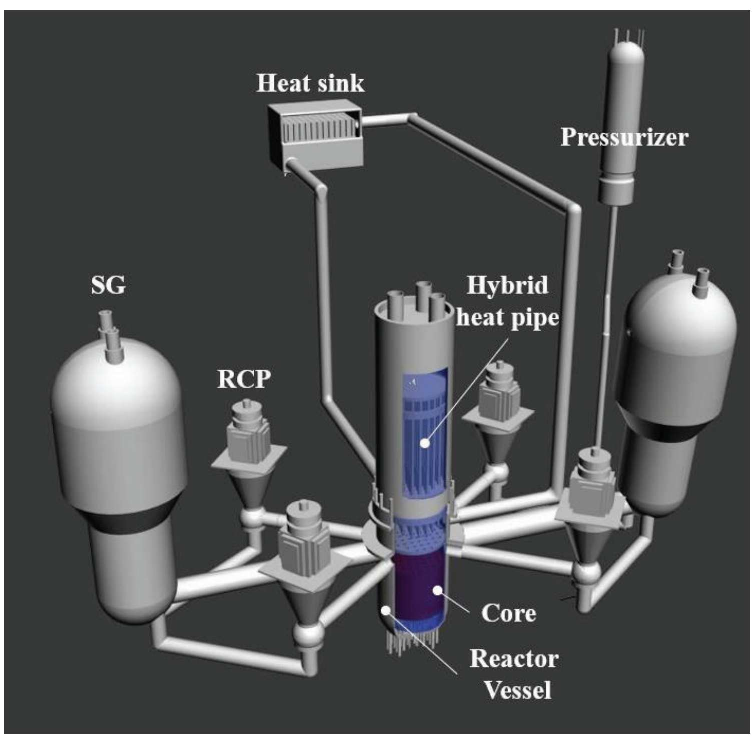


Figure 1. Systematic design of hybrid heat pipe as Passive IN-core Cooling system (PINCs)

In this study, a hybrid heat pipe is introduced as a PINCs and the design features are demonstrated for a heat pipe containing a neutron absorber. Using a commercial CFD code, single hybrid heat pipe was simulated to evaluate thermal performance in designated operating conditions. In addition, one-dimensional reactor transient analysis was conducted by calculating the temperature change in the coolant inside reactor pressure vessel using MATLAB.

2. NUMERICAL METHOD

For evaluating the thermal performance of the hybrid heat pipe as a PINCs with unique design features and cooling performance in the reactor, two-step numerical analysis was performed. One is a single hybrid heat pipe simulation with commercial CFD code, ANSYS-CFX, and the other is a one-dimensional thermal hydraulic reactor transient analysis by calculating the coolant temperature inside reactor pressure vessel using MATLAB.

2.1. Single hybrid heat pipe simulation

The physical domains of the single hybrid heat pipe simulation consist of a solid region for the metal cladding and neutron absorber structure, a porous region for the wick structure, and a fluid region for the vapor path and wick structure, shown in Figure 2. For the single hybrid heat pipe simulation, permeability of the wrapped screen wick as wick structure, K can be calculated as follows [7]:

$$K = \frac{d^2 \varepsilon^3}{122(1-\varepsilon)^2} \tag{1}$$

, where d is the wire diameter and ε is the wick porosity. In the study, 100 mesh screen wire mesh was considered as wick structure and its porosity and permeability is 0.62 and 1.92×10^{-10} m^2, respectively. Operation condition of the heat pipe can be determined by the saturation condition of working fluid, water. The saturation temperature and pressure of the water considered in this study were 209 °C and 20.17 bar, respectively. The reactor condition at the accident situation was reflected on the heat pipe performance calculation. Table I shows the domain setting of the single hybrid heat pipe simulation.

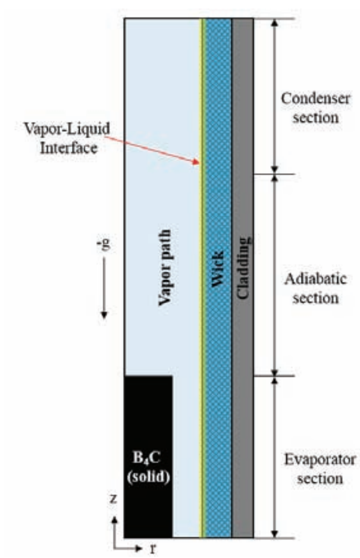


Figure 2. Physical domain of single hybrid heat pipe simulation

Table I. Domain specification of the single hybrid heat pipe simulation

Parameter	Value
Length of hybrid heat pipe (evaporator: adiabatic: condenser)	4.3 m: 7.5 m : 4 m
Working fluid	Water
Operating pressure	20.17 bar (T_{sat}=209 °C)
Wick	100-mesh wire screen
Porosity [7]	0.62
Permeability [7]	1.92×10^{-10} m^2

For the single hybrid heat pipe simulation, three-dimensional steady state continuity, momentum, and energy equations were solved for the solid, vapor, and liquid regions. For the wick structure, Darcy's law was used to govern the momentum equation for liquid flow in porous media with porosity and permeability as the momentum loss term. To consider the effect of the latent heat from phase change, mass source, sink and energy source, sink terms were added to the evaporator and condenser region. For vapor region, the continuity, momentum, and energy equations can be written as follows [8]:

$$\nabla\cdot(\rho\mathbf{U})=0 \tag{2}$$

$$\nabla\cdot(\rho\mathbf{U}\otimes\mathbf{U})=-\nabla p+\nabla\cdot\left(\nabla\mathbf{U}+(\nabla\mathbf{U})^T-\frac{2}{3}\delta\nabla\cdot\mathbf{U}\right) \tag{3}$$

$$\nabla\cdot(\rho\mathbf{U}h)=\nabla\cdot\left(k\nabla T\right)+\nabla\mathbf{U}+S_E \tag{4}$$

The radial vapor velocity boundary conditions were considered for mass change from evaporation and condensation at the vapor-liquid interfaces given by [9]:

$$v_e=+\frac{q}{2\pi r_{\text{int}}L_e\rho_v h_{fg}} \tag{5}$$

$$v_a=0 \tag{6}$$

$$v_c=-\frac{q}{2\pi r_{\text{int}}L_c\rho_v h_{fg}} \tag{7}$$

The temperature of vapor-liquid interface for all sections was calculated by Clausius-Clapeyron formula [10]:

$$T_{\text{int}}=\frac{1}{\dfrac{1}{T_{sat}}-\dfrac{R}{h_{fg}}\ln\left(\dfrac{P_v}{P_{v,sat}}\right)} \tag{8}$$

In the wick region, Darcy's law inside porous media was considered.

$$\nabla\cdot\left(\rho(\mathrm{K}\cdot\mathbf{U}\otimes\mathbf{U}\right)-\nabla\cdot\left(\mu_e K\cdot(\nabla\mathbf{U}+(\nabla\mathbf{U})^T-\frac{2}{3}\delta\nabla\cdot\mathbf{U}\right)=\varepsilon S_M-\varepsilon\nabla p \tag{9}$$

Since the heat transfer characteristics of the hybrid heat pipe is important in this study, the detailed behavior of a bubble and condensed liquid droplet were neglected. However, the phase change of working fluid at the liquid-vapor interface was considered as a source term in the momentum and energy equations. For modeling phase change phenomenon, source and sink terms were added at the wick in evaporator and condenser regions [11].

$$S_e = -\frac{q}{\pi\left(\left(r_{\text{int}}+t\right)^2 - r_{\text{int}}{}^2\right)L_e} \tag{10}$$

$$S_c = +\frac{q}{\pi\left(\left(r_{\text{int}}+t\right)^2 - r_{\text{int}}{}^2\right)L_c} \tag{11}$$

The effective thermal conductivity of porous media with saturated liquid wick can be calculated as [7]:

$$k_{eff} = \frac{k_f[(k_f + k_s) - (1-\varepsilon)(k_f - k_s)]}{[(k_f + k_s) + (1-\varepsilon)(k_f - k_s)]} \tag{12}$$

In this simulation, following assumptions were considered for the hybrid heat pipe simulation to solve the continuity, momentum and energy equations.

1) Incompressible laminar flow for both liquid and vapor;
2) The vapor region for the vapor path and the liquid region for wick structure are separated, and mass and energy transfers occur only at the liquid-vapor interface;
3) All vapor and liquid are considered to be saturated, and the properties of the liquid and vapor are constant.

2.2. 1-D reactor transient analysis

One-dimensional reactor transient analysis was performed to evaluate the cooling performance of the hybrid heat pipe as PINCs as calculating the temperature of the coolant inside the reactor pressure vessel after reactor shutdown using MATLAB. When all ECCS fail in a station blackout accident, a steam generator can remove the immediate decay heat from the fuel for a moment by evaporation of remaining coolant in primary circuit. Therefore, target time of the hybrid heat pipe is after no more heat sink is available. At that time, the amount of decay heat is about 45 MW. In reactor transient calculation, time was considered after 3000 sec from reactor shutdown, when the hybrid heat pipe is the only way of cooling reactor after shutdown. Decay heat generated after shutdown can be expressed as:

$$\frac{P(t)}{P_o} = 0.066\left[t^{-0.2} - (t+t_s)^{-0.2}\right] \tag{13}$$

Right after the control rod drops off, the decay heat is approximately 6 – 7 % of the normal operating power and continuously decreased exponentially. In equation (13), the normal operation power P_0 is used as 3836 MWth for APR-1400, t is time since reactor started, and t_s is approximately 1.57×10^8 s, assuming 5-year operation. Total mass of coolant in the RPV is approximately 308 tons at 155 bar. A one-dimensional coolant volume was assumed for calculating temperature change due to decay heat, and its initial temperature is assumed to be 320 °C. The pressure inside the RPV was assumed to be constant at

155 bar, because the pressure oscillates between 14.8 MPa and 17.0 MPa because of the evaporation of coolant due to the temperature increase and steam leakage through the PORV (Pilot Operated safety and Relief Valve) in the pressurizer. Core uncovery was indicated by the core water level reaching 4 m, which implies that 200 tons of water is evaporated. The boiling of coolant was indicated when the temperature of the coolant reached the saturation temperature for a given pressure.

MATLAB script was written for evaluating the cooling performance of the hybrid heat pipe as a PINCs during SBO accidents and associated condition by calculating the temperature change of coolant inside the reactor pressure vessel. By integrating the equation (14) with respect to time, final temperature of coolant was determined. Coolant temperature was calculated as:

$$MC_{p,l}(T_f - T_{bulk}) = \int_0^{t_f} P(t)dt - \int_0^{t_f} Q_{HP}dt \tag{14}$$

Overall thermal resistance of the hybrid heat pipe can be obtained from total amount of heat removed by the hybrid heat pipe from the result of a single hybrid heat pipe simulation. Total amount of heat removed by hybrid heat pipe can be expressed as follows:

$$Q_{HP} = \frac{T_f - T_c}{R_{total}} \tag{15}$$

3. RESULTS AND DISCUSSIONS

Numerical analysis of hybrid heat pipe was performed by solving continuity, momentum and energy equations of each domain to evaluate the thermal performance. In the simulation, reactor environment conditions were considered as boundary condition. Right after reactor shutdown and stopping of coolant flow, the bulk temperature of the coolant near the active core is approximately 320 °C. Heat removal rates through evaporator and condenser section was estimated by equation (16).

$$Q_{HP} = k\frac{dT}{dr} \tag{16}$$

, where k is the thermal conductivity of the cladding of hybrid heat pipe. With the given conditions, a total of 18.20 kW of heat is transported by the hybrid heat pipe. To evaluate the overall thermal performance of the hybrid heat pipe, the total thermal resistance was calculated. From the predicted results, the total thermal resistance of the hybrid heat pipe is 0.015 °C/W.

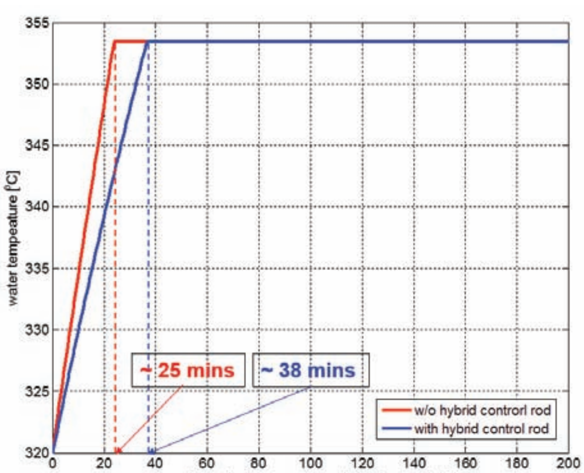
The interface temperature between the vapor and liquid was 217.34 °C at maximum and 201.25 °C at minimum so that boiling and condensation inside the hybrid heat pipe cause no operation problem considering the saturation temperature of the working fluid. Specifically, the maximum vapor velocity is approximately 6 m/s at the end of the evaporator side, which is at the location of sudden increase of the cross sectional area in the vapor path due to the cylindrical B_4C pellet in the evaporator region. This implies that vapor flow can have behavior of the local transition flow. The maximum vapor pressure drop in the vapor path is approximately 350 Pa between the evaporator end sides, which means that an additional model for predicting flow in the vapor path may be necessary for a more accurate solution. However, in this study, this aspect can be negligible in evaluating overall thermal performance of the hybrid heat pipe. The thermal performance for the hybrid heat pipe is summarized in Table. II.

Table II. Summary of single hybrid heat pipe simulation

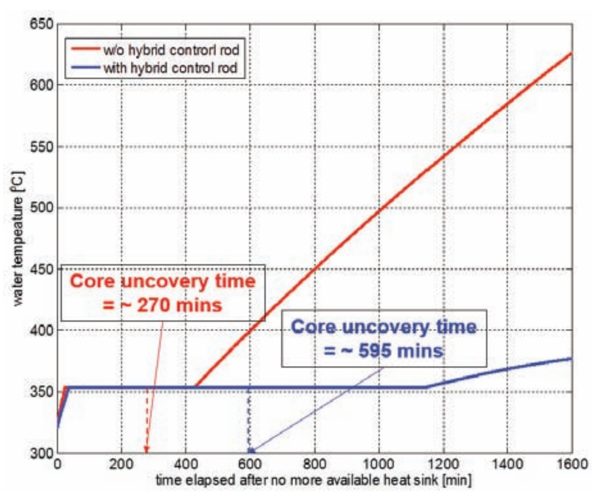
Parameters		Values
T_{avg}	Evaporator region	320 °C
	Adiabatic region	256 °C
	Condenser region	50 °C
T_{int}	Maximum	217.34 °C
	Minimum	201.25 °C
Total amount of heat removed		18.20 kW
Total thermal resistance		0.015 °C/W

Figure 3 (a) and (b) show the results of reactor transient analysis with respect to the time elapsed after heat sink is no longer available for the normal and the hybrid heat pipe cases. For the normal reactor, the time to reach the saturation temperature, which is 344.76 °C at 155 bar is only approximately 25 min. The Hybrid heat pipe delays the time required for coolant boiling by approximately13 minutes. Unfortunately, in both of two cases there was a possibility of the core uncovery. However, core uncovery was delayed by 325 minutes with the hybrid heat pipe compared to the normal reactor, therefore, the response time to an unexpected situation can be secured.

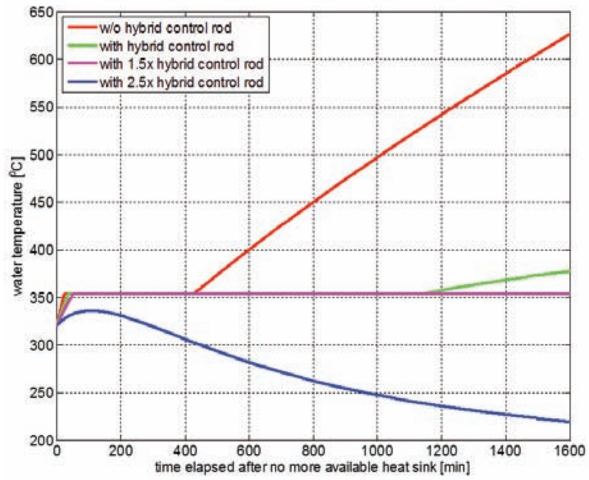
Figure 3 (c) shows the reactor coolant temperature after the heat sink is no longer available after reactor shutdown for the normal reactor case, and for the reactor with several improved hybrid heat pipe cases. With the enhanced hybrid heat pipe having 1.5 times and 2.5 times improved capacity, results showed no core uncovery within one day from considered point, which is sufficient to cope with an emergency situation to the reactor. In particular, the hybrid heat pipe having 2.5 times improved capacity continue cooling the reactor and the coolant temperature was maintained below the boiling temperature. For this case, coolant temperature started to decrease after 150 min. Figure 3 (d) shows the comparison between amount of decay heat after loss of the heat sink and removed heat by the hybrid heat pipe. The maximum reactor temperature is 335.83 °C and the maximum amount of heat removal is 35.64 MW.



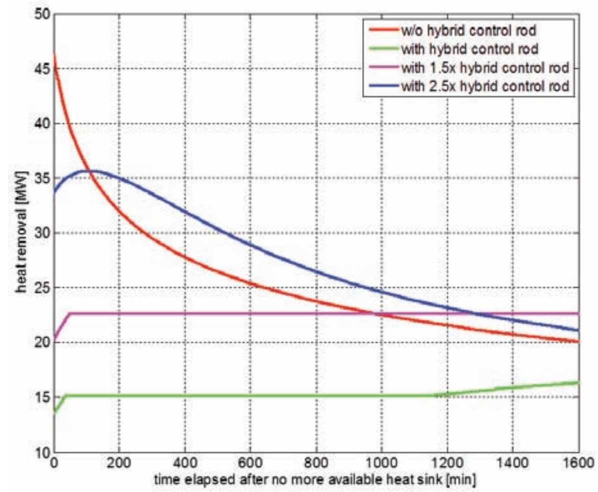
(a) Reactor temperature change and time required to boil the coolant



(b) Reactor temperature change and time required to core uncovery



(c) Reactor temperature change with various capacity of hybrid heat pipe



(d) Heat generated for normal reactor and amount of heat removed by hybrid heat pipe of various capacities

Figure 3. Result of reactor transient analysis compared with normal reactor and reactor with hybrid heat pipe

4. CONCLUSIONS

Hybrid heat pipe with a combination of heat pipe and control rod was suggested as a passive in-core cooling system. The hybrid heat pipe has the distinct feature that it can be a unique solution to cool the reactor when the depressurization process is impossible and a conventional ECCs cannot inject refueling water into the RPV. It contains a neutron absorber material, so it can stop the reactor and at the same time, remove decay heat in core. For evaluating the concept of a hybrid heat pipe, thermal performance was analyzed numerically using CFD and one-dimensional transient analysis was conducted. From single hybrid heat pipe simulation, the hybrid heat pipe can transport heat of 18.20 kW from the core inside to the outside, and the total thermal resistance of hybrid heat pipe was 0.015 °C/W. Because of the unique features of a long heat pipe and high-temperature high-pressure condition, the hybrid heat pipe design should consider the additional effects of local transitional flow of vapor. For evaluating cooling performance of the hybrid heat pipe as PINCs, reactor transient analysis was performed to calculate the temperature change after no more heat sink for decay heat removal is available. From one-dimensional reactor transient analysis, time required to boil the water in the RPV is delayed approximately13 minutes, and core uncovery time is delayed by 5.4 hours with the hybrid heat pipe, assuring the sufficient response time in an accident situation. If the hybrid heat pipe has 2.5 times improved cooling capacity, it can continue cooling the reactor and preventing evaporation of the coolant with no core uncovery within one day. Therefore, the hybrid heat pipe can work well as PINCs, combined with a control rod and heat pipe having the same drive mechanism as a traditional control rod in a station blackout accident.

NOMENCLATURE

C_p	heat capacity	[J/kg K]
h	latent heat of vaporization	[J/kg]
k	thermal conductivity	[W/m K]
K	permeability	[m2]
M	total mass of coolant	[kg]
L	length	[m]

p	pressure	[Pa]
P	reactor power	[MW]
q	heat input	[W]
r	radius	[m]
R	gas constant	[J/mol K]
R_{total}	thermal resistance	[°C/W]
S	source term	[W/m3]
t	thickness	[m]
T	temperature	[K]
U	velocity	[m/s]

Greek symbols

ρ	density [kg/m3]	
ε	wick porosity	
μ	dynamic viscosity	[Pa s]

Subscripts

0	normal operation (full power)
avg	average
c	condenser region
e	evaporator region
eff	effective
f	final
HP	hybrid heat pipe
int	liquid-vapor interface
l	liquid state of working fluid
s	solid state of wick material or startup time
sat	saturation state
v	vapor state of working fluid
w	wick

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