



Entransy definition and its balance equation for heat transfer with vaporization processes



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ABSTRACT

Entransy balance equations and the corresponding optimization principles for heat conduction, heat convection and thermal radiation have been established. This paper develops the entransy balance equation for a low speed steady flow system with vaporization processes. The definition of enthalpy entransy for a substance from solid state to vapor state is proposed. The expressions of entransy and entransy dissipation are derived with differential volume element integration and the concept of enthalpy entransy. The heat transfer between a vaporization stream and a hot stream in a heat exchanger is also analyzed with the entransy approach. The theoretical results show that the minimum entransy-dissipation-based thermal resistance always leads to the maximum heat exchanger effectiveness. A numerical example compared with the entropy generation approach verifies the theoretical analyses. For a heat exchanger network undergoing vaporization processes, the minimum entransy-dissipation-based thermal resistance is proved to be applicable as the optimization criteria for the maximum heat exchange rate. The minimum entransy-dissipation-based thermal resistance principle is applied to two numerical cases for the thermal conductance distribution optimization to obtain the maximum heat exchange rate.

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1. Introduction

Owing to the large latent heat and inherently high heat transfer coefficients, vaporization processes are widely applied to air-conditioning [1–3], electronic components [4–6], power system [7,8], heat pipes [9], etc. The enhancement and optimization of the vaporization processes are of great importance to the energy efficiency improvement, energy savings and high heat flux removal. The vaporization is the process from liquid to vapor, containing evaporation and boiling. In theoretical research, the coupled heat and mass transfer model is usually used to analyze the evaporation processes [2,3], while the bubble dynamics is a common method for analyzing boiling processes [10]. Numerical simulations [11–14] and experiments [15] have been conducted in order to verify and to assist the theoretical researches in the optimization of vaporization processes. For instance, a three-dimensional, vapor-liquid two-phase model of proton exchange membrane fuel cell (PEMFC) was numerically investigated by Cao et al. [12]. Zhang et al. [13] established the physical and mathematical models for film cooling at high pressure, in which the vaporization process occurs at the subcritical regime. A pore-scale numerical model

based on the lattice Boltzmann method was also developed for multiphase reactive transport with phase transitions [14].

In the last decade, Guo et al. [16] introduced the concept of entransy that describes heat transfer ability, which has many applications in heat transfer optimization [17], such as heat conduction [16–21], heat convection [22,23], thermal radiation [24,25], heat exchangers [26–29] and thermal networks [30–32]. For instance, Chen [33] applied the entransy theory to optimizing many heat conduction problems. Yu et al. [23] used the field synergy principle and entransy dissipation extremum principle to analyze the turbulent flow and heat transfer performance of the composite porous material numerically. Han et al. [28] applied the minimum thermal resistance based on the entransy dissipation to optimizing and designing the heat exchanger structure. Feng et al. [34] applied the entransy dissipation extremum principle to thermal insulation constructal optimizations and their research indicated that the optimal constructs of the insulation layers with minimum entransy dissipation rate improves their global thermal insulation performance. The entransy method has been further developed for mass transfer optimization [2,3,35,36] and heat-work conversion optimization [37].

There are several reports on heat transfer optimization with phase change based on the concept of entransy, including solid-liquid phase change [38,39], condensation [40] and vaporization

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[1–3]. For the vaporization processes, the concept of moisture entransy [1,2] was also defined to analyze the coupled heat and mass transfer processes in evaporation cooling system. Jiang et al. [1] discussed and explained several typical heat and mass exchanging processes based on the entransy concept. Chen et al. [2,3] optimized the evaporative cooling system based on the concepts of entransy dissipation and thermal resistance.

However, the initial definition of entransy only accounts for sensible internal energy at a temperature [16]. It is dependent on temperature. Qian et al. [41] proposed the concept of two-phase entransy and optimized heat exchangers with vaporization processes based on it but there is no derivation of entransy balance equation for vaporization processes. The entransy theory and its applicability to vaporization processes require further development.

This paper investigates the heat transfer with vaporization processes and the applicability of entransy theory to heat transfer optimization with vaporization processes. The corresponding entransy balance equation is developed. The entransy dissipation is also derived by differential volume element integrations and the definition of absolute enthalpy entransy, respectively. The minimum entransy-dissipation-based thermal resistance principle is proved to be applicable to the heat exchanger between a hot stream and a liquid–vapor two-phase stream. A heat exchanger network with vaporization processes is then optimized with the extremum entransy dissipation principle and the minimum entransy-dissipation-based thermal resistance principle.

2. Entransy, entransy balance equation, entransy dissipation for heat transfer with vaporization processes

An open steady flow with vaporization processes is shown in Fig. 1. There is no inner heat source, and only saturated flow boiling happens during the vaporization processes. Assume that the flow velocity is low, so the Mach number is small, flow pressure change is small in the vapor region, and then the fluid is assumed to be incompressible respectively in the liquid, vaporization and vapor regions. The densities and specific heat capacities at the liquid state and vapor state are constant. The heating effect due to viscous dissipation can be neglected for low velocity flow. The system inlet flow rate of the fluid is \dot{m} , and the inlet temperature is T_{in} . As shown in Fig. 1, the fluid in the left region of the system is at liquid state, the fluid in the middle region is at vaporization state and that in the right region is at vapor state. The volumes of the regions are V_l , V_v and V_g , respectively. The heated liquid changes into vapor in the vaporization region. Assume that the vaporization temperature is T_{gas} , and the latent heat of vaporization is γ_{hv} (J/kg). The temperature of the whole vaporization region is just the vaporization temperature T_{gas} . The outlet temperature of the system is T_{out} if the outlet flow is vapor.

As the latent heat is absorbed in the vaporization region, the energy conservation equation of the vaporization region is

$$h_{v-out} = h_{v-in} + \gamma_{hv}, \tag{1}$$

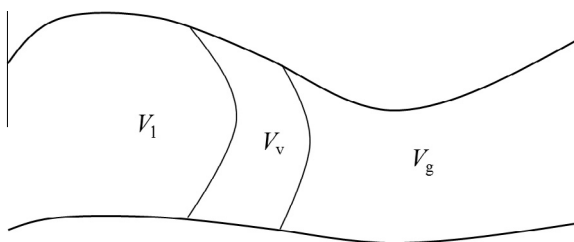


Fig. 1. The schematic of the open steady flow system.

where h_{v-in} is the inlet specific enthalpy of the vaporization region, which is also the outlet specific enthalpy of the liquid region, and h_{v-out} is the outlet specific enthalpy of the vaporization region, which is the inlet specific enthalpy of the vapor region as well.

Considering a certain differential volume element in the liquid or vapor region, the energy conservation gives

$$\mathbf{u} \cdot \nabla(\rho h) = -\nabla \cdot \mathbf{q}, \tag{2}$$

where h is the specific enthalpy of the fluid, ρ is the fluid density, \mathbf{u} is the velocity vector of the fluid, and \mathbf{q} is the heat flux vector. Cheng et al. [42] defined the concept of enthalpy entransy, the differential expression is

$$dg_H = Tdh, \tag{3}$$

where T is the temperature, Multiplying Eq. (2) with temperature T leads to

$$\mathbf{u} \cdot T\nabla(\rho h) = -T\nabla \cdot \mathbf{q}. \tag{4}$$

Combining Eq. (4) with Eq. (3), the entransy balance equation for the differential volume element is

$$\mathbf{u} \cdot \nabla(\rho g_H) = -\nabla \cdot (\mathbf{q}T) - (-\mathbf{q} \cdot \nabla T). \tag{5}$$

The term on the left-hand side of Eq. (5) is the entransy variation rate in the differential volume element due to the mass exchange across the boundaries. It is also the net entransy exchange rate due to the net mass flow exchange out of the differential volume element. The first term on the right-hand side (including the minus sign) is the net entransy flow into the differential volume element due to the heat exchange on the boundaries. The second term on the right-hand side $-\mathbf{q} \cdot \nabla T$ is the entransy dissipation rate in the differential volume element. Eq. (5) indicates that part of the net entransy flow by heat flow into the volume element is brought out of the element by mass flow, and the rest is dissipated.

As the specific heat capacities for the liquid and the vapor are assumed to be constant, the relations between the specific enthalpies and temperatures are $dh = c_{p,l}dT$ and $dh = c_{p,g}dT$, in which $c_{p,l}$ and $c_{p,g}$ are the specific heat capacities for the liquid state and vapor state at constant pressure, respectively. Combining Eqs. (4) and (5), the entransy balance equations for the differential volume element in the liquid region and vapor region can be simplified as

$$\mathbf{u} \cdot \nabla\left(\frac{1}{2}\rho_l c_{p,l}T^2\right) = -\nabla \cdot (\mathbf{q}T) - (-\mathbf{q} \cdot \nabla T), \tag{6}$$

$$\mathbf{u} \cdot \nabla\left(\frac{1}{2}\rho_g c_{p,g}T^2\right) = -\nabla \cdot (\mathbf{q}T) - (-\mathbf{q} \cdot \nabla T), \tag{7}$$

where ρ_l is the liquid density and ρ_g is the vapor density. Integrating Eq. (6) on the whole liquid region leads to the entransy balance equation of the liquid region. The integrated entransy balance equation of steady flow with constant thermophysical properties without phase change [43] is

$$\oint_{\Sigma_l} \frac{1}{2}\rho_l u c_{p,l} T^2 dS + \oint_{\Sigma_l} q T dS = \iiint_{V_l} (-\mathbf{q} \cdot \nabla T) dV, \tag{8}$$

where dS is an area element on the boundary surface Σ_l of the liquid volume V_l , and the heat flux q is positive if it goes into the volume. The first term on the left-hand side of the equation is the net entransy flow accompanying fluid flow into the liquid region. The second term is the net entransy flow that is carried into the liquid region by the heat flow through the boundary. The right-hand side term is the total entransy dissipation in the liquid region. Furthermore, for the liquid region of Fig. 1, there is

$$\frac{1}{2}\dot{m}c_{p,l}T_{in}^2 - \frac{1}{2}\dot{m}c_{p,l}T_{gas}^2 + \oint_{\Sigma_l} q T dS = \iiint_{V_g} (-\mathbf{q} \cdot \nabla T) dV. \tag{9}$$

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