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An entransy based method for thermal analysis and management of high heat density data centers

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0. Introduction

With the fast development of new IT techniques (e.g. cloud service, AI, mobile internet), the past few years have witnessed a sharp increasing demand for massive data storage, computing and processing. A large number of data centers have been built and updated in consequence, resulting in a dramatic rise of power demand. During the past 10 years, the peak pay load of rack level has been increased from less than 10 kW to over 30 kW in average [1]. Meanwhile, due to the widely use of highly integrated chips (such as CPU and GPU), the peak heat flux of IT equipment also showed a steep rise to nearly 50 W/cm^2 [2], which has been commonly seen in high performance commercial blade servers. With increasingly higher heat flux and more compact layout, hot spot is no longer a locally over-heating phenomena, but a fetal threat to the thermal health of entire data center [3,4]. Consequently, over 40% of annual operating cost has been spent on air-conditioning [5] and this ratio is expected to exceed 60% in next five years [5]. Now that thermal management significantly affects the operational security and cost of data centers, to find a more effective solution with better energy performance becomes a key issue for thermal management of future high heat density data centers [6–8].

Data center thermal management aims to maintain facility temperature and energy cost within a reasonable range, through the adjustment and optimization of IT payload, facility layout, air flow pattern, operating mode and cooling configuration. Traditionally, the fundamental theory of data center thermal analysis contains heat transfer rules and thermodynamic laws only [9–12]. Based on which, various numerical and experimental models have been developed to predict energy flow and temperature distribution inside data centers, from chip level to room space [13–20]. In state of the art, most of the models are based on *Navier-Stokes* equation for flow computing, coupled with continuity and heat transfer equations, with different boundary and initial conditions [21–23]. Other models use new evaluating indicator (*SHI*, *RHI*, *RCI*), revised algorithm (POD, ROM, artificial network method) or advanced data processing tools to achieve faster calculation, better evaluation of the overall performance of data center thermal management, further optimization on operating parameters, or more accurate fitting of test data [24–26].

Besides of theoretical research, many case studies have been introduced in data center thermal design and management [27–30], some of which have succeed to offer guidance to improve cooling efficiency, reduce hot spot and energy cost with specified boundary and operating conditions.

Recently, as more urgent needs for cooling energy benefits emerged, analysis on the availability of outdoor free cooling potential and maximum energy efficiency becomes focused issues. Consequently, much attention has been paid to thermodynamic based theories. As typical examples, exergy theory has been widely used to optimize thermal management and improve data center energy performance [31–33]. Exergy method gives revised air flow pattern, power plant and payload allocation in data centers, maximizes the potential of useful work, based on the principle of least exergy loss/entropy generation.

1. Entransy theory

1.1. Entransy theory introduction

Recent years, Guo et al. [34–41] proposed a new physical quantity called entransy, to represent heat transport potential, by analogy with electric and gravity field. In electric filed, with the same potential difference, the more quantity of electricity a body carried,

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the more field work occurs, resulting in more loss of potential energy. By analogy, in temperature field, the heat flux q driven by temperature difference δT always causes an irreversible dissipation, representing a kind of potential energy loss. In temperature field, such loss can be quantified as $\Delta J = q \times \delta T$. ΔJ is defined as entransy dissipation, which represents the irreversible loss of heat transport ability. Furthermore, this definition means that, in temperature field, the entransy J can be represented by heat flux q at temperature T as $J = q \times T$. Thus, the entransy dissipation ΔJ during a heat transport process, from initial (q_1, T_1) to final (q_2, T_2), can be quantified as $\Delta J = q_1 \times T_1 - q_2 \times T_2$.

For continuous process in temperature field

$$\Delta J = \int_{T_1}^{T_2} q(T)dT \tag{1-1}$$

Eq. (1-1) offers a new graphical expression for entransy flow and dissipation, called *T-Q* chart. Fig. 1 is a *T-Q* chart representing a steady state open system with heat transport process inside, with a heat/cold source of constant temperature T_h/T_c. Two fluids are involved, with the inlet and outlet temperature of T_{in}/T_o and T_c/T_l respectively.

For heat transfer process from heat source (T_h) to fluid (T_{in}/T_o), according to Eq. (1-1), the corresponding entransy dissipation ΔJ_h is

$$\Delta J_h = \int_{T_{in}}^{T_o} (T_h - T)dq = \int_{T_{in}}^{T_o} (T_h - T)(cmdT)$$
$$= cm(T_o - T_{in})\left[T_h - \frac{1}{2}(T_o + T_{in})\right] = q\Delta T_{mean} \tag{1-2}$$

In Eq. (1-2), *cm* represents mass and heat capacity flow rate of the fluid, W/K; q is the total heat removed, W; ΔT_{mean} refers to the mean temperature difference between heat source and fluid, K. ΔJ_h is graphically illustrated by the yellow region in *T-Q* chart in Fig. 1.

For heat transfer process between two fluids, in which one fluid is cooled from T_o to T_{in}, while the other is heated from T_c to T_l, according to Eq. (1-1), the corresponding entransy dissipation ΔJ_l is (see Fig. 2)

$$\Delta J_l = \int_{T_{in}-T_c}^{T_o-T_l} \Delta T dq = \int_{T_{in}-T_c}^{T_o-T_l} \Delta T d(KF\Delta T)$$
$$= \frac{1}{2}KF[(T_o - T_l)^2 - (T_{in} - T_c)^2] \tag{1-3}$$

The total transported heat q can be expressed as

$$q = \int dq = \int_{T_{in}-T_c}^{T_o-T_l} KFd(\Delta T) = KF[(T_o - T_l) - (T_{in} - T_c)] \tag{1-4}$$

Bring Eq. (1-4) back to Eq. (1-3), the entransy dissipation ΔJ_l is finally obtained as

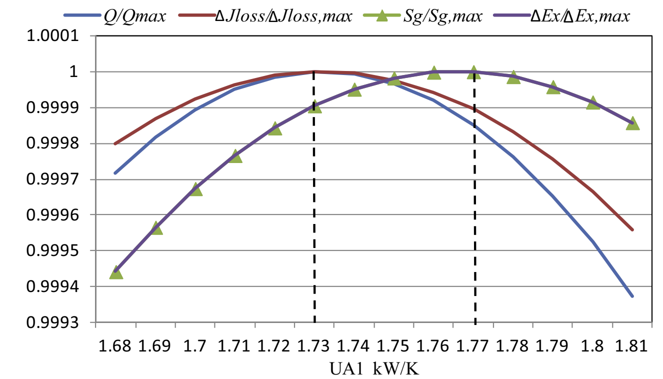

Fig. 2. Variation of transported heat, exergy loss, entropy generation and entransy dissipation with increment of heat transfer ability UA_1.

$$\Delta J_l = q\frac{1}{2}[(T_o - T_l) + (T_{in} - T_c)] = q\Delta T_{mean} \tag{1-5}$$

In Eqs. (1.3)-(1.5), *KF* represents heat transfer ability for each integrating unit, W/K, which is assumed to be constant during heat transport. ΔT is the temperature difference of two fluids for each integrating unit, K. ΔJ_l is illustrated by the green region in *T-Q* chart in Fig. 1.

Using the same derivation as Eq. (1-2), the entransy dissipation between the fluid and cold source ΔJ_c can be rewritten as

$$\Delta J_c = \int_{T_c}^{T_l} (T - T_c)(cmdT) = cm\int_{T_c}^{T_l} TdT - cmT_c\int_{T_c}^{T_l} dT$$
$$= cm(T_l - T_c)\left[\frac{1}{2}(T_l + T_c) - T_c\right] = \frac{1}{2}q(T_l - T_c) \tag{1-6}$$

ΔJ_c expressed by Eq. (1-6) is represented by the blue region in *T-Q* chart in Fig. 3.

Bring Eqs. (1.2), (1.5) and (1.6) into Eq. (1-7) to get the total entransy dissipation ΔJ as represented by Eq. (1-8).

$$\Delta J = \Delta J_h + \Delta J_l + \Delta J_c \tag{1-7}$$

$$\Delta J = q\left[T_h - \frac{1}{2}(T_o + T_{in})\right] + q\frac{1}{2}[(T_o - T_l) + (T_{in} - T_c)]$$
$$+ \frac{1}{2}q(T_l - T_c) = q(T_h - T_c) \tag{1-8}$$

Eq. (1-8) reveals the behavior characteristics of entransy flow and dissipation for a steady state open system, with at least two fluids involved.

With Eq. (1-8) and *T-Q* chart, entransy theory turns a complex heat transfer system into a simple mathematical field model, with all thermal behavior quantified by entransy flow and dissipation.

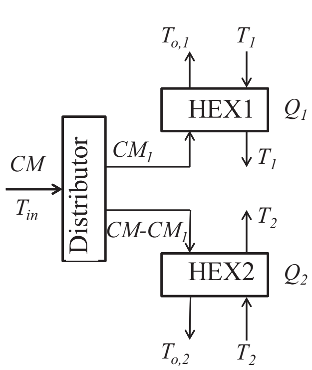

Fig. 1. Solo heat transfer process for verification.

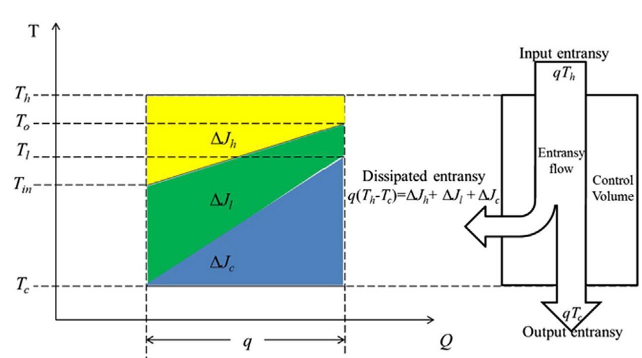

Fig. 3. T-Q chart of entransy flow and dissipation.