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Research paper

Low-grade heat and its definitions of Coefficient-of-Performance (COP)

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HIGHLIGHTS

- Importance of thinking heat extraction for high energy efficiency in buildings.
- The concept of Thermal COP and the determination of its (maximum) Kelvin limit.
- Key to find the sweet spot of using heat pump is thinking *general* heat extraction.
- *triadCOP* & *eThermalCOP* are measure of energy transformation in the triad framework.

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ABSTRACT

Use of fire for low grade heat, still widely practiced today, is wasteful because it is based on the principle of heat production – which should have become an outmoded idea post-Carnot for low grade heat application as an exergy analysis will readily conclude. Instead of application of exergy analysis, a new thermodynamic analysis resulting from the unification of Kelvin's energy principle and the entropy principle, formulated recently (called the entropic theory of heat), is applied here to reexamine the problem of building heating. Other than improving envelope heat resistance, conventional building efficiency gain is predominantly obtained by improving HVAC efficiency (i.e., boiler efficiency); our finding shows that there is in fact large room in improving the building heating operation surpassing 100% boiler efficiency, as demonstrated by the large value of the Kelvin limit (the theoretical upper bound of Thermal COP). This theoretical possibility of generous amount of heat from fire suggests additional possibilities of heat from primary energy other than fire, and the disclosure of these possibilities by applying the triad framework in the entropic theory of heat in terms of alternative definitions of Coefficient of Performance (COP). Consideration of such alternative COPs suggests real possibility of efficiently and cost effectively obtaining low grade heat from primary energy.

1. Introduction

Considering a heat source from a fire of combustion gas of the amount, $\dot{m}_f c_P (T_f - T)$, where $\dot{m}_f$ is the gas mass flow rate, T_f the adiabatic flame temperature, and T the temperature of a space, what will be the physically-possible maximum low-grade heat it can supply to the space at T? This paper is a theoretical study of low grade heat from fire as well as a discussion of low grade heat from energy sources other than fire.

Mankind discovered the use of fire before the dawn of civilization. The invention of steam engine by James Watt and Matthew Boulton (among others) and the discovery-creation of the theory of heat by Carnot, Joule, Kelvin and Clausius marked the second use of fire by mankind for the production of power. It is this fire according to Amory Lovins in *Reinventing Fire* [1] that is one of causations of the Industrial Revolution – and a key driving force behind every necessities (food, dwelling, transportation, water …) modern society takes for granted today. In 1776 Boulton was quoted [2] to say, “I sell here, sir, what all the world desires to have – power.” History has proven him right. But, what the world desires to have also includes heat: the world needs power and heat.

Fire or power is needed for the direct production of high-grade (high temperature) heat required for industrial and manufacturing uses. Low-grade heat is another matter: whereas the “emphasis on the mechanical definition of heat” [3] in thermodynamics encourages the view that low-grade heat, high-grade heat, and

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mechanical energy are "equivalent" energetically speaking — the real lesson from Carnot is that low-grade heat flow, high-grade heat flow, and mechanical energy flow of the same flow rate are different due to their very different entropy flow rates: high, low, and zero respectively. Entropically and economically speaking, the direct use of fire (i.e., high-grade heat) for *producing* low-grade heat as in boilers is wasteful. Thomson (later Lord Kelvin), the inventor of heat pump, understood this and put it this way,

> It appears … there would be perfect economy of the heat of the fire if all the heat … were applied to heating the air pumped in, and if none of this heat were allowed to escape by conduction through the air passages. It is not my present object to determine how nearly in practice this … may be approximated to; but to point out how the limit which has hitherto appeared absolute, may be surpassed, and a current of warm air at such a temperature as is convenient for heating and ventilating a building may be obtained mechanically … by means of a steam engine, driven by a fire burning actually less coals than are capable of generating by their combustion the required heat; and secondly, to show how, with similar mechanical means, currents of cold air, such as might undoubtedly be used with great advantage to health and comfort for cooling houses in tropical countries, may be produced … [4].

Lord Kelvin, or William Thomson, showed in the paper that low-grade heat can be obtained by "a fire burning actually less coals than are capable of generating by their combustion the required heat." That is possible because the boiler process and the heat pump process are different: heat is *produced* in boilers while heat is *extracted* (or, *managed* by being moved from one body to another body) in the composite systems of heat-engine and heat-pumps.

Practical devices for refrigeration were developed by Coleman [4], and for air-conditioning by Carrier [5,6]. These compression refrigeration cycle based devices and other kinds of cooling devices are all based on heat extraction principle. Heating, in contrast, can be obtained based on either heat extraction or heat production. Because of that, method for heating is *chosen* largely on economic ground. In a 1930 article [7], Haldane reported his experimental finding that a heat pump can operate in both cooling mode *and* heating mode. Though technically feasible the application of heat pump for heating has not found its "sweet spot," however, as its market-penetration is still limited today.

We argue here two points for helping to find this sweet spot of heat pump operation. The first is this: Since the beneficial use of heat pump depends on the interaction of heat pump with the building (which is itself a thermal system), we need, in addition to the science of the device, a science of the building thermal processes, two important aspects of which are the heat transfer process across the *building envelope* (the physical separator between the interior and the exterior environments of a building including components: foundation, roof, walls and their insulation layers, and doors and windows), and the building conditioning operation. John Scofield in his 2012 Congressional testimony "The science behind green building rating systems" [8] noted the lack of scientific basis for building rating. We identified that a critical flaw in building thermal science and building performance rating was inability in delineating the building *envelope* heat transfer loss from the building *operation* (cooling and heating) loss. Gain in better understanding of this first point concerning building thermal processes will suggest below that we should also examine the underlying process that makes heat pump attractive to uncover how to make the use of heat pump even more attractive, which will be the second point presented in Section 4 concerning the true nature of heat pump process.

This paper reports a powerful thermodynamic analysis method developed in the new entropic theory of heat in Section 2. The method is then applied in Section 3, which describes a thought experiment by constructing "reversible production" of low-grade heat from fire so that the resulting irreversible loss in a building is due to heat transfer process across its envelope alone. With this delineation of operation from envelope, this paper introduces a definition of building operation performance in terms of *Thermal COP* and the corresponding determination of reversible Thermal COP (the Kelvin limit of Thermal COP). In the discussion section, Section 4, with the encouragingly high value in the Kelvin limit for obtaining heat from fire it is suggested that when heat extraction is viewed in terms of the triad framework in the entropic theory of heat, the possibility of using heat pump as a part of general heat extraction system emerges with corresponding alternative definitions of COPs. Consideration of such alternative COPs suggests real possibility of efficiently and cost effectively obtaining low grade heat from primary energy. The paper closes with concluding remarks in Section 5.

2. The entropic theory of heat

Carnot's discovery of the second law of thermodynamics is usually considered to be marred by his use of material caloric in accordance with the prevalent caloric theory of heat at the time. The orthodox view, that heat is not material and is equivalent to work and that this fact was discovered by Davy, Mayer and Joule, was first offered by Thomson in the opening paragraphs in his paper "On the dynamical theory of heat" (1851) [9]. Thomson then succeeded in obtaining the expression for the reversible work produced in a Carnot cycle, [10].

$$W_{Carnot-Kelvin} = Q_H\left(1 - \frac{T_C}{T_H}\right) \tag{1}$$

That is,

$$(\eta_{th})_{Rev} = \left(1 - \frac{T_C}{T_H}\right)$$

Equation (1) suggests the dyad of heat and work energy-transformation, though it does have a tacit element of triad thinking (see the comment on Equations (1) and (15) in Section 4 below). It is important to note that the most critical step Thomson took in his intellectual journey toward the celebrated Eq. (1) was revealed in the draft of the 1851 paper cited by Thomson's biographers Smith and Wise [11]:

> The difficulty which weighed principally with me in not accepting the theory so ably supported by Mr. Joule was that the mechanical effect stated in Carnot's Theory to be *absolutely lost* by conduction, is not accounted for in the dynamical theory otherwise than by asserting that *it is not lost*; and it is not known that it is available to mankind. The fact is, it may I believe be demonstrated that the work is *lost to man* irrecoverably; but not lost in the material world. Although no destruction of energy can take place in the material world without an act of power possessed only by the supreme ruler, yet transformations take place which removes irrecoverably from the control of man sources of power which, if the opportunity of turning them to his own account had been made use of, might have been rendered available.

In this remarkable passage Thomson realized that there are two fundamental ideas concerning energy: its conservation (the