CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 7

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Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 7*. Department of Civil Engineering, Aalborg University.

A Framework to Assess Exergetic Efficiency for Thermal Comfort

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Abstract

Exergy analysis is usually used to supplement traditional thermodynamic efficiency based on only energy balances in evaluating overall system performance. It examines the connections between different components, and is therefore helpful in preventing efficiency losses due to inadequate system integration, which formed the foundation of low exergy (LowEx) building design: using lower exergy for space heating/cooling allows for larger efficiency as well as overall economic benefits. A few recent studies have been able to link human comfort with the low exergy concept, arguing that the lowest human exergy destruction rate warrants thermal comfort. The current studies available and the complexity of the models they proposed warrants a review. We therefore examine three such human exergy exchange models in this paper. Models from Shukuya, Wu and Mady were compared against one another for synergies and discrepancies. A conceptual framework was then proposed to include the exergy consumption of human body as the final link in exergy supply chains for LowEx systems. This framework would then be validated conceptually for its usages in existing LowEx building systems. It was concluded that the proposed framework could work for some types of systems, but may require additional development to serve as an alternate for LowEx building systems across the board.

Keywords – Exergy Analysis; Thermal Comfort (key words)

1. Introduction

Introduced to rationalize the energy usages in the early 1970s, exergy analysis has been applied to both building and community levels in studies over the last few decades [1]. As can be found in the exergy analysis on both conventional and renewable power plants, the output from power plants is usually high quality energy. This creates a significant margin of exergy saving potential for system designs, which is in particular important for the United States where about 54% of total energy consumption in an average U.S. home goes to heating and cooling [2]. Such awareness triggered research interests on low-exergy building system designs, or more specifically, buildings supported by localized low-quality energy. Such systems are known to be widely applicable, provide higher indoor comfort, have better energy efficiency as well as space efficiency [3].

The occupants as the main beneficiary of such system, however, have yet to be included in efficiency calculations. Although a few models have been proposed by some studies, their intended use was either in comfort or physiology studies. Shukuya et al. challenged the status-quo by proposing a correlation between the minimum exergy destruction rate and thermal comfort [5]. It could be viewed as a great opportunity to include the human body exergy exchange model in a new framework to evaluate LowEx building systems. Building on these concepts, it is possible for us to consider proposing a potential framework of evaluating the building system's exergetic efficiency in terms of providing thermal comfort for occupants.

2. Exergy Basics

Exergy efficiency for various energy systems have been defined as efficiencies based on exergy (or second law efficiencies). Despite being one widely accepted definition, exergy efficiencies are generally calculated in one of two ways: ’brute-force’ and ’functional’ [6]. A ’brute-force’ exergy efficiency is defined as the ratio of the sum of all output exergy terms to the sum of all input exergy terms, while a ’functional’ exergy efficiency is defined as the ratio of the exergy associated with the desired energy output to the exergy associated with the energy expended to achieve the desired output. In other words, one being at a top-down approach while the other is a bottom-up definition. The exergy efficiency presented in this article will be the top-down exergy efficiency.

Exergy should always be evaluated with respect to a reference environment, i.e. when the system is in equilibrium with the environment. A state that satisfies the mechanical, thermal and chemical equilibrium without any possibility of spontaneous change or interactions between its components can be considered an actual reference state [7].

3. Exchange between human body and surroundign environment

3.1 Existing Models:

Many human exergy destruction models are developed from human entropy generation models, as summarized in Table 1. Most of these models were either designed to account for the activity levels within a very long time frame [8], using physiological parameters [9], (which requires continuous measurement), or looking at molecular level of chemical reactions [10], ultimately providing extensively detailed theoretical support for the human body exergy destruction rate model to be developed.

Author	*Highlight*	*Gagge Two-Node Model*	*Thermal Sensation*	*Year*
Shukuya	Incoporates Vapor Expansion	Yes	Yes	2000
Prek	Entire life span	Yes	No	2010
Aoki	S_{gen} as function of age	No	No	1989
Batato	Lifespan entropy generation	No	No	1990
Boregowda	Objective Thermal Comfort Index	No	Yes	2001
Rah-man	Compre-hensive entropy flux model	No	No	2007
Silva	Accounts for ATP generation	No	No	2009

Three prominent human body exergy models from Shukuya[5], Wu[11] and Mady[12] were further developed from these entropy generation models.

Quantitatively comparing the three models, some significant improvement has been made over the course of last decade, where increased precision and decreased complexity of models can be observed, leading to a possibility of calculating the overall exergy efficiency targeting to provide maximum thermal comfort for occupants.

More explicitly, a few major discrepancies between the models include: when accounting for the metabolism and work, the Mady's model based its calculation on the molecular level ATP generation utilizing the amount of gas inhaled and exhaled instead of the Shukuya and Wu model as in Eq. 1 where a constant metabolic rate is assumed:

$$B_{QM} = M(1 - \frac{T_0}{T_b}) \tag{1}$$

$$B_M = B_{reac}\text{-}B_{prod} = 9558 m_{O_2} + 3928 m_{CO_2} \tag{2}$$

Similarly, the Mady model also provided more reasonable accounts for the exergy destruction through respiration by using not generic pressure assumption, but rather the exhaled & inhaled gas components:

$$\Delta B_{res} = m_{res} \sum_i (y_{i,ex} c_{p,i} (T_{ex}\text{-}T_0\text{-}T_0 \ln\left(\frac{T_{ex}}{T_0}\right) + y_{i,ex} R_i T_0 ln\,(\frac{P_{i,ex}}{P_{i,0}})) \tag{3}$$

The Shukuya model, on the other hand, despite being a much more comprehensive model, had many terms that were deemed insignificant by the other models such as the exergies of the water generated from metabolism and their dispersion to the air in both the core and the shell, etc.

Comparing the three models, a trend towards simplifying the exergy model can be observed: Building on the Shukuya model, Wu suggested that the expanding vapor should not be considered significant since the heat required for vapor expansions is much less than the heat required for the evaporation of liquid water, quoting a 1983 study by Monteith to back their claim[13]. Mady et al., on the other hand, quoted their own work two years earlier, suggesting that the highest level of exergy destruction does not take place during lower temperature, but rather higher temperature.

Overall, the Shukuya and Wu model are comparable since they are both constructed on similar premises. The Mady model, on the other hand, was novel in the derivation and adaptation of many terms but lacks clarity and repeatability. It did not, for example, explicitly cite the Gagge two-node model yet according to some of the terms that were being used in the paper (such as $P_{w,sk}$ and $P_{e,cl}$) [14], the two-node assumption was still used to model the human body. Similarly, the calculation method of the Q_r and Q_c was never specified in Mady's publication. Qualitatively speaking, the Wu model provided effective simplification towards the Shukuya model while the Mady model provided many new aspects to look at the activity-related exergy destruction.

There is also currently no agreed-upon comfort indicators for human exergy analysis: Shukuya and Wu both argued thermal neutrality is achieved at the time of minimum exergy destruction - this, however, was challenged by experimental results from Mady despite the fact that the prior assumption was verified by Schweiker et al. against other existing comfort models [15]. Also, none of the models were explicit on the system boundaries selected for the human exergy exchange models - whether it is sufficient to stop at the clothing or skin level and what should be considered the reference state.

Also, all three exergy exchange models used the minimum exergy destruction rate as the indicator of perceived thermal neutrality, which was already demonstrated to be slightly off the actual perceived neutral thermal comfort[16].

3.2 Proposed integration of human body exergy with system exergy efficiency

The building sector traditionally uses more electricity generated at high economic and environmental costs from primary energy resources rather than renewable energy resources. Therefore it has a relatively large potential for the implementation of low exergy systems. In fact, according to [4], beyond the common exergy supply chain in Figure 1, the idea of including the occupants as an element in exergetic efficiency analysis already exists in the system thinking. It just needs to be emphasized as an objective rather than a component in the calculation for exergetic efficiency. The final exergy destruction in the proposed integration can therefore be optimized not only on the system side based on losses to the environment (at the reference state), but also on maintaining optimal exergy destruction rate for the human body, as is illustrated conceptually in Fig. 2.

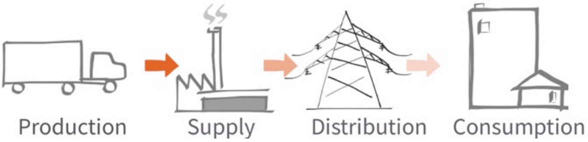

Fig. 1 Traditional flow chart for exergetic efficiency calculation from chain of demand

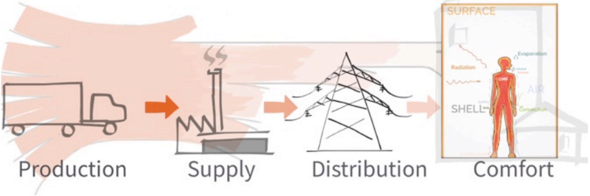

Fig. 2 Proposed framework of exergetic efficiency calculation framework with the Sankey diagram for U.S. energy supply breakdown in 2014 adapted in the background

3.3 Framework of integration

The proposed framework for the integration of human body exergy model with any existing exergy analysis model is to simulate the system performance for a typical design day (heating or cooling) for the fluctuation of air and surface temperatures, then use those directly in the calculation of real time exergy destruction rate using the human body exergy model to optimize delivery of comfort rather than standard system analysis based on predefined heating or cooing comfort conditions that fix room exergy consumption illustrated in Fig. 1. The density and activity level of the occupants will have to be assumed for this process to obtain a more reasonable result and to facilitate further calculation for exergy efficiency. The benefit of such a framework is a trajectory of exergy efficiency throughout the day with time stamps for the peak and valley based on occupant conditions. This framework could be extremely important since exergy analysis already shows that the actual demand of energy from buildings is low-grade, and the human body exergy model will also shift the focus away from generic building demand to an occupant comfort demand. Both the occupants' comfort and system performance can be tied back to the low-exergy concept. The future aim is to develop methods that support this framework so that both the exergetic efficiency of system components and the exergy delivered to occupant can be obtained during dynamic simulation. Said framework is proposed to support development of an overall system simulation such that calculates exergy efficiency for the design condition and also the dynamic exergy analysis [17], which could also provide a more fundamental method of quantifying thermal comfort as well as the exergetic efficiency of the building system components as the outputs of the analysis.

3.4 Framework potential in the context of current low exergy system research

For heating systems, low exergy systems are often realized through low temperature lift: A heat pump can operate at high coefficient of performance (COP) by using a small temperature lift to raise the theoretical cap of Carnot efficiency. When the heat source, (regardless of it being ground, water, solar or waste heat) is closer to the supply temperature for heating, larger amounts of heat per unit electricity can be moved. Balta et al., for example, investigated a low exergy heating system supplemented by ground-source heat pump system with pre-selected boundary conditions [18]. Thanks to the latest development in simulation engines such as EnergyPlus, more detailed models with customizable heating system are now possible, making it easier to adapt to the proposed framework by simulation.

For more integrated systems, such as the new LowEx modeling method that is proposed by Açikkalpet in 2014, the framework can work seamlessly since the investigation was limited to one single room, making the simulation and exergetic analysis not only possible but also computationally feasible [16]. In order to understand the impact of different objects for optimization (thermal comfort/energy efficiency) for the operational strategies for low exergy building, the simulation could be computationally intensive with the continuous optimization of schedule [20].Yet since the simulation results can be verified, the actual exergy analysis can be a continuous process of verification of model to provide more insights to the usage of the proposed framework.

There are systems that the proposed framework may not be adequate to evaluate such as aa direct expansion solar assisted heat pump system (DX-SAHP), that supports both the heating system and the hot water demand for the household [18]. It cannot be generalized because space heating and hot water are not both addressed in the human body exergy model. To evaluate performance such as the effective production of hot water of a hybrid system like this may require including the output hot water as a part of the targeted exergy supply.

4. Conclusions and Discussions

To sum up, a review of human body exergy modeling shows it is still developing, and can be improved by combining the currently available models. By comparing the three human exergy exchange models term by term, Shukuya's model appears to be the most comprehensive but contains many terms that are depreciated by other models, while Wu's model stands out with the best referenced on how the model was constructed despite a few caveats in its basic assumptions (such as referencing Monteith's study on water vapor expansion being a term that can be omitted). Mady's model has the largest potential to be adapted for future exergy model construction for its improvements on many components (such as that for metabolism and respiration). A framework can therefore be proposed that combines the three models to simultaneously address human body exergy as the final objective within a system exergy efficiency analysis.

Finally, it is hard to define the actual boundary of the human body. Although the model can be defined as in Figure 2, the mass exchange between the human body and the surrounding environment could be extremely hard to quantify.

It was therefore determined that to benefit future studies, a framework that accounts for human exergy destruction rate to be included into the exergetic analysis for building systems- such that humans are included not only as a source but also the aim for exergy supply- An analysis that quantifies the different exergy exchange rate between the human body and the surrounding environment to determine the most prominent parameters could be extremely valuable. Moreover, additional forms of exergy efficiencies may also be necessary to account for different demands aside from providing thermal comfort for the occupants, such as the hot water supply for households or the electricity generated by some systems such as solar PV or geothermal hybrid systems.

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