Discussion Regarding the Principles of Exergy Analysis Applied to HVAC Systems

Ren-Chengqin¹, Tang-Guangfa², Li-Nianping³ and Yang-Jing⁴

¹Professor, College of Mechanical and Automotive Engineering, Hunan University
Changsha, Hunan 410082 P. R. China (renchengqin@163.net)
²Professor, College of Civil Engineering, Hunan University
Changsha, Hunan 410082 P. R. China
³Professor, College of Civil Engineering, Hunan University
(linianping@sina.com)
⁴College of Mechanical and Automotive Engineering, Hunan University

Abstract
Exergy is another name for available energy that measures the ability of the energy source to produce useful work. This article provides an analytical review of some pertinent works in HVAC application. Some general conclusions can be obtained. Exergy efficiency is more rational than energy efficiency; exergy analysis is more helpful than energy analysis for locating and evaluating available energy saving potentials, identifying opportunities for improvements in system design and establishing cost effective system maintenance programs. In addition, an unusual selection of dead–states novel to HVAC applications is suggested, which simplifies the exergy analysis by eliminating the necessity of calculating the exergy of water at ambient temperature (T₀). Such a selection will also make it easier to evaluate the precooling capacity of moist air. In this paper, the authors also suggest a functional classification to break down the HVAC project in a hierarchical structure for exergy analysis. The HVAC system is considered as an exergy service system that provides exergy for pure consumption in exergy consumer systems such as conditioning space. The exergy service system can be further broken down into different components. The exergy flows are also classified according to their functions as source exergy flow and service exergy flow to assist the evaluation of the performance of the systems or components. Relevant principles of exergy analysis are discussed. Finally, examples are calculated to demonstrate the application and the reasonability of the above propositions.

Keywords: principles of exergy analysis; HVAC systems; functional classification; exergy efficiency; dead–state

Introduction
Useful energy consumed in Heating Ventilating and Air Conditioning (HVAC) accounts for approximately 20% of total consumption of energy sources these days. Effective use of useful energy is especially important. We may still be accustomed to evaluate the performance of HVAC systems based on the first law of thermodynamics. The energy we need to maintain the operation of these systems is, indeed, the available energy. Since Gibbs introduced this concept, the theory has been developed rapidly and popularized in a variety of engineering fields. Exergy is another name for available energy in thermodynamic terms. Much literature has also been devoted to the research of exergy analysis in HVAC. An analytical review of it will help in understanding the principles of application. Further, the classifications of systems and useful energy flows are discussed in this article to assist in the appropriate application of these principles. Also, an unusual selection of dead–states novel to HVAC applications are reasonably suggested.

Analytical review
Exergy measures the ability of energy to work. For fluid flow, the exergy represents the work that can be produced in a reversible process that is designed to bring it to a state of equilibrium with the environment. It can be generally represented as:

\[ ex = (h - T₀s) - (h₀ - T₀s₀) \] (1)

Because the moist air encountered in HVAC may be approximately treated as an ideal gas mixture, its flow exergy may be represented as follows:
The heat flow exergy is:

\[
\text{ex} = (C_{pa} + \omega C_{pv}) (T - T_0) \ln \frac{T}{T_0} + (1 + 1.608 \omega) R_a T_0 \ln \frac{P_0}{P_a} + R_a T_a ((1 + 1.608 \omega) \ln \frac{P_0}{P_a + 1.608 \omega})
\]

(2)

Similar forms can be found in many textbooks, Kenneth (1995) and Bejan (1988). Where \( T, p, \omega \) denote the temperature, pressure, humidity ratio of moist air respectively, and \( C \) and \( R \), the specific heat and gas constant. The subscript “0” indicates the dead state. In addition, there are many other exergies. The heat flow exergy is:

\[
ex = (1 - T_0/T) \delta q
\]

(3)

The exergy of electrical or mechanical work is straightforward. It is equal to the work itself. For many other exergies, we can refer to thermodynamics textbooks, Kenneth (1995), Bejan (1988) and Yunus et al. (1988).

Wepfer et al. (1979) gave a detailed conclusion of the expressions of various exergies in HVAC. In discussing the exergy efficiency (or second law efficiency, or effectiveness), a general expression is used as follows with \( \eta \) denoting the available energy:

\[
\eta_a = \frac{A_{\text{product}}}{A_{\text{product}} + A_{\text{destroyed}} + A_{\text{lost}}}
\]

\[
= \frac{A_{\text{supplied}}}{A_{\text{supplied}} - A_{\text{destroyed}} - A_{\text{lost}}}
\]

(4)

Here, the destruction of available energy is classified into two groups: available energy destroyed due to the inner irreversibility of the system and the amount lost in effluents. Examples of adiabatic mixing, steam-spray humidification, adiabatic evaporation, dehumidification and direct expansion cooling are calculated. Valuable information of exergy destruction may be extracted from the tabulated results. Thus, improvements are implicitly suggested. However, some assistant devices are also evaluated with that definition of the exergy efficiency, which is very low but insignificant for the overall system. In addition, the atmospheric state was selected as the dead state. The effluent of a small amount of condensed water would result in a great loss of exergy even if it is a well-known fact that this effluent is unimportant in the effective use of available energy. Thus, it leads to an understimation of exergy efficiency.

Tan et al. (1986) devised, ingeniously, the exergy-enthalpy diagram of refrigerant R22 with the aid of auxiliary diagrams applicable to various ambient conditions. Thus, exergy loss in the refrigeration cycle can be determined very easily and quickly with reasonable accuracy for practical purposes. They also gave a definition of exergy efficiency that was expressed flexibly as follows:

\[
\eta_{\text{ex}} = \frac{\text{exergy desired for the system}}{\text{exergy needed for the desired effect of the system}}
\]

\[
= \frac{\text{exergy destroyed for the system}}{\text{exergy needed for the desired effect of the system}}
\]

(5)

However, its application in various complicated air conditioning systems was not discussed because of their concentration.

Tsaros et al. (1987) gave a specified definition of exergy efficiency for each unit or set of units or systems in analyzing a typical residential heat pump. Though no general definition was given in the literature, two types can be found by carefully examining all the definitions. For energy conversion systems or subsystems, the efficiency is defined as the ratio of the exergy produced by conversion to the exergy needed to maintain the conversion process. For any other device, the efficiency is defined as the ratio of the efficiency of the conversion system with this device to that without this device or with zero exergy lost in this device. Calculation results of exergy losses and efficiencies are tabulated, showing the breakdown of inefficiencies by subsystems and devices. The results have motivated several recommendations for improving the overall system. However, the atmospheric state is selected as the dead state for calculating the exergy of moist air.

Franconi et al. (1999) provide an example of applications of exergy analysis in large integrated systems. In their work, the performance of two HVAC distribution systems (CAV and VAV) was evaluated using the first and second law thermodynamics. The prototypical office building is a ten-story, five zones (four perimeters and one core) building located in Washington, D.C. Exergy balance shows the advantage of VAV systems over CAV by reducing the exergy depleted in cool coil, reheat coils and fans. Negative exergy load occurs during the spring season to all five zones and during winter to the south perimeter zone and the core zone (That is because the zones have cooling loads and the ambient temperature is cooler than the zone temperatures. If a reversible engine is imaginatively placed between the zone to be conditioned and the environment, useful energy can be obtained and thus, the exergy load is negative.) The second-law efficiencies for the two systems are low (and negative!). This indicates great opportunity for making thermodynamic improvements in air distribution system design. Exergy analysis is also used to help in diagnosing malfunctions by identifying the changes in trends of system exergy input requirements, justifying system recommissioning and pinpointing optimized system operation. Thermoeconomics uses thermodynamics in conjunction with economic analysis to achieve improved cost benefit and quality in design.

Tozer et al. (1999) introduced the cost term into the exergy analysis to establish cost-effective design parameters.
Thus, at least two general conclusions can be obtained. Exergy efficiency is more rational than energy efficiency; exergy analysis is more helpful than energy analysis for locating and evaluating available energy saving potentials, identifying opportunities for improvements in system design and establishing cost effective system maintenance programs. However, the dead-state selection, the proper classifications of systems and energy flows and the performance evaluation of systems are still worth further discussion.  

**Dead state**  
Usually, the atmospheric state \((T_0, P_0, \omega_0)\) is selected as the dead state. However, when the atmospheric air is not saturated, it still possesses available energy. Let us consider a reversible process as shown in Fig.1.

### Fig.1 Schematic of a reversible process

- **Unsaturated atmospheric air** \((T_0, P_0, \omega_0)\), 1kg dry air + \(\omega_0\) kg water vapor
- **Water** \((\omega_0 - \omega_0)\) kg, at \(T_0, P_0\)  

\[ W = \text{ex}_w + (\omega_0 - \omega_0) k \text{ex}_w - \text{ex}_{\omega_0} \]  

Where subscript “\(\omega_0\)” represents the state with saturated humidity ratio at atmospheric temperature. According to Eq. (2), \(\text{ex}_{\omega_0} = 0\)kJ/kg (a) and

\[ \text{ex}_{\omega_0} = R_a T_0 [(1 + 1.608 \omega_0) \ln \frac{1 + 1.608 \omega_0}{1 + 1.608 \omega_{\omega_0}} + 1.608 \omega_{\omega_0} \ln \frac{\omega_0}{\omega_{\omega_0}}] \]  

For water, as shown by Kenneth (1995) and Bejan (1988), the exergy is

\[ \text{ex}_w = -R_a T_0 \ln \frac{p_{\omega_0}}{p_{\omega_{\omega_0}}} \]  

Where \(p_{\omega_0}\) is the water vapor pressure of the unsaturated atmospheric air and \(p_{\omega_{\omega_0}}\) is the saturated water vapor pressure at \(T_0\). Substituting equation (7) and (8) into equation (6), we learn that:

\[ W = R_a T_0 [(1 + 1.608 \omega_0) \ln \frac{1 + 1.608 \omega_0}{1 + 1.608 \omega_{\omega_0}} + 1.608 \omega_{\omega_0} \ln \frac{\omega_0}{\omega_{\omega_0}}] \]  

If imaginary state \((T_0, P_0, \omega_0)\), being saturated at atmospheric temperature, is selected as dead state, \(\text{ex}_w\) and \(\text{ex}_{\omega_0}\) are all equal to zero. On contrary, we have:

\[ \text{ex}_{w} = R_a T_0 [(1 + 1.608 \omega_0) \ln \frac{1 + 1.608 \omega_0}{1 + 1.608 \omega_{\omega_0}} + 1.608 \omega_{\omega_0} \ln \frac{\omega_0}{\omega_{\omega_0}}] \]

\[ (10) \]

It shows that the exergy of unsaturated atmospheric air \(\text{ex}_{\omega_0}\) is equal to the maximum useful work \(W\). Such a selection will obviously simplify the exergy analysis. The underestimation of exergy efficiency mentioned in section 2 will be avoided because the exergy of water at ambient temperature equals zero. By replacing \(\omega_0\) in equation (2) with \(\omega_{\omega_0}\), we get

\[ \text{ex} = \frac{(C_p + \omega C_p)}{(T - T_0) \ln \frac{T}{T_0}} + (1 + 1.608 \omega_0) R_a T_0 \ln \frac{p}{p_0} + R_a T_0 [(1 + 1.608 \omega_{\omega_0}) \ln \frac{1 + 1.608 \omega_{\omega_0}}{1 + 1.608 \omega_0} + 1.608 \omega_{\omega_0} \ln \frac{\omega_0}{\omega_{\omega_0}}] \]  

\[ (2') \]

In addition, it is easy to evaluate the precooling capacity of moist air (such as outdoor air or exhaust room air as secondary air) using Eq. (2').  

### Classification of systems and exergy flows

Any HVAC project can be broken down into two main parts. One is the conditioned space and the other the conditioning system. The conditioning system works to convert different energy sources to the required forms and provide services needed by the conditioned space. Hence, any conditioned space can be classified as a consumer system. On the contrary, the conditioning system will be classified as a service system or conversion system. Further, this service system can still be broken down into different parts.

- **HVAC project**
- **Conditioned space (consumer system)**
- **HVAC system (conversion system or service system)**

**Conversion subsystems** (such as refrigerator, heat pump, compressor, indoor coil, heaters, fan, pump or combined with their associated hardware or assistant devices, etc.)

**Nonconversion or assistant devices** (such as expansion valve, connecting pipe, outdoor coil, plenum, etc.)

Fig.2. Hierarchical structure of HVAC project

They are classified as conversion subsystems or
nonconversion or assistant devices. All these classifications are shown schematically in Fig. 2.

For a consumer system or conditioned space, the calculation of exergy load is needed. Because the pressure difference between the conditioned space and the environment is usually small, this load mainly includes approximately two terms: thermal and chemical exergy loads. Thermal exergy load \(LE_{th}\) for sensible heating of a room with a sensible heating load \(Q\) can be calculated by the following equation:

\[
LE_{th} = (1-T_p/T)Q
\]

The chemical exergy load \(LE_{ch}\) for room dehumidifying is the product of humidifying load \(W\) and the partial derivative of Eq. (2) with respect to \(\omega\).

\[
LE_{ch} = 1.608R_0\ln\left(\frac{(1+1.608\omega_0)Q}{(1+1.608\omega_0)Q_0}\right) - W
\]

If \(Q<0\) and \(T>T_p\), \(LE_{ch}\) will be negative as described in section 2. This results, as Franconi et al. (1999) have pointed out, from large buildings which, often have a cooling load when it is cold outside. Similarly, if \(W<0\) and \(\omega<\omega_0\), \(LE_{ch}\) will be negative. This occurs if there is a dehumidifying load while it is drier outside. The exergy load for fresh air also includes a thermal and chemical exergy load, but the total exergy load of fresh air can be simply calculated as the difference between the exergies of room air and fresh air.

The service system provides the exergy needed for the consumer system. The conversion system or subsystem converts different energy resources to the required forms or converts useful energy from one stream to another. In general definition of exergy efficiency, both Eq. (4) and (5) are acceptable if the numerator and the denominator are properly calculated. The authors suggest the following general definition as used implicitly by Tsaros et al. (1987):

\[
\eta_{ex} = \frac{\text{exergy produced by the conversion, or exergy product}}{\text{exergy needed to maintain the conversion process, or exergy supply}}
\]

However, the exergy product and the exergy supply need further explanation. This will be discussed in a later paragraph.

Any assistant device is associated with a conversion system or subsystem. The exergy efficiency is defined as:

\[
\eta_{ex} = \frac{\eta_{ex, \text{associated upper system with this device}}}{\eta_{ex, \text{associated upper system without this device or with zero energy lost in this device}}}
\]

In HVAC, the exergy flows need also to be properly classified in order to obtain a proper evaluation of exergy product and supply. The input electricity or mechanical work is obviously classified into exergy supply. Reduction of the exergy of the secondary flow streams that is used to heat or cool, or humidify or dehumidify the primary flow streams should also be classified into exergy supply. The relevant exergy flow can be regarded as source exergy flow. While the increase of exergy of primary flow streams is classified into exergy product. The relevant exergy flow is regarded as service exergy flow, because it is provided to serve the needs of other systems. The theory of such a classification can be shown schematically in figure 3.

**Calculation example and summary**

Let us imagine an office of 30 m² conditioned with a residential air conditioning unit. Table 1 shows the indoor and outdoor conditions. The conditioning loads are estimated according to the usual practices. Performance data of the air conditioning unit is also estimated but represents the average performance of different manufacturer’s products approximately. Tables 2 and 3 show these data and the calculated exergy information for heating and cooling mode respectively. In these tables, energy required for room heating represents sensible heating or cooling load and energy required for room humidifying represent latent heating or cooling load. The air supply temperature is

| Table 1. Indoor and outdoor conditions |
|---------------------------------------|
| Conditioning | Indoor air temperature (°C) | Outdoors air relative humidity (%) |
| Indoor | 20 | 52.8% |
| Outdoor | 35.8 | 57.5% |

| Table 2. Energy requirement and exergy information for heating mode |
|---------------------------------------------------------------|
| Conditioned space | Room heating | Room humidifying | Fresh air | Whole air conditioning unit |
|-------------------|-------------|-----------------|---------|---------------------------|
| Energy required (kW) | 3.82 | -0.7 | 3.87 | 6.99 |
| Exergy required (kW) | 0.2997 | -0.02794 | 0.1194 | 0.4467 |
| Exergy depleted (kW) | 0.4467 | 0.1194 | 0.4467 | 2.3 |
| Exergy efficiency \(\eta_{ex}\) | 87.6% | 19.42% |
The exergy efficiency is the ratio of the exergy of the air supply to the depleted electricity.

Figure 4 shows another example of conversion as discussed by Wepfer et al. (1979). The exergy is converted from water to air. Exergies and efficiency are calculated and compared with those obtained by Wepfer et al. (1979) in table 4. The results show that the effluent loss or exergy of condensed water (water 5) by the current selection of dead state is much smaller than that given by Wepfer et al. More exactly, such a small amount of condensed water even at low temperature plays a negligible role in the condition of the system’s energy use. It is obviously consistent with our usual practice and hence, more reliable. On the contrary, the exergy product is increased and more properly evaluated.

The above examples show clear classifications of systems and energy flows and their roles in exergy analysis. The effect of proper selection of dead state is also demonstrated.

Table 3. Energy requirement and exergy information for cooling mode

| Conditioned space | Whole air conditioning unit |
|-------------------|----------------------------|
| Room heating      | Room Humidifying           |
| Energy required (kJ/h) | -3.9 | -0.7 | -3 | -7.6 |
| Exergy required (kJ/h) | 0.1345 | 0.04772 | 0.1194 | 0.356 |
| Exergy depleted (kJ/h) | 0.356 | 2.97 |
| Exergy efficiency $\eta_{ex}$ | 84.7% | 12% |

Table 4. Exergy information for cooling and dehumidification

| Exergy (kJ/h) | This paper | Wepfer, W. J. et al |
|---------------|------------|-------------------|
| Air 1         | 3.854      | 0                 |
| Air 2         | 6.611      | 1.59              |
| Water 3       | 18.4567    |                   |
| Water 4       | 12.536     |                   |
| Water 5       | 0.0035     | 1.22              |
| Exergy product | 2.757   | 1.59              |
| Exergy supply | 5.92      | 6.12 *            |
| Exergy efficiency | 45.05% | 25.98% |

* This data is subject to small errors

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