ISSN 1392–1207. MECHANIKA. 2017 Volume 23(1): 70–77

Exergy efficiency of a ventilation heat recovery exchanger at a variable reference temperature

Vytautas Martinaitis*, Juozas Bielskus, Karolis Januševičius***, Paulius Bareika******

**Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania, E-mail: vytautas.martinaitis@vgtu.lt*
***Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania, E-mail: juozas.bielskus@vgtu.lt*
****Vilnius Gediminas Technical University, Saulėtekio al. 11, 10223 Vilnius, Lithuania, E-mail: karolis.janusevicius@vgtu.lt*
*****Amalva, UAB Vilnius, Lithuania, E-mail: paulius.bareika@amalva.lt*

crossref http://dx.doi.org/10.5755/j01.mech.23.1.17678

1. Introduction

As a science and a branch of engineering, thermodynamics is used to determine and increase the efficiency of thermal processes. To rephrase Lord Kelvin, it is difficult to improve a process without knowing its efficiency and it is important to evaluate the quantity and the quality of streams. The first and the second laws of thermodynamics help to explore the full range of energy forms in qualitative and quantitative matters. At first, thermodynamic analysis was used to study the performance of thermal engines in order to evaluate heat engines and turbines as well as their internal processes. The International Energy Agency has brought more attention to the analysis based on the second law and its benefits for the development of building service systems. This approach had been adopted previously by Baehr in 1962 [1]; Szargut and Petela in 1965 [2, 3]; Bejan in 1970 [4], Borel in 1984 [5]; but in the context of low energy buildings and limited possibilities of renewable energy resources, the application of thermodynamic analysis offers a great advantage. The opportunity to highlight harmful sources of irreversibility encourages developing technologies as well as exploring and comparing design alternatives.

In this paper which is focused on exergy analysis in the context of the building energy performance assessment, an important contribution is made to the interaction between energy chains, reference temperature and exergy efficiency.

1.1. Energy transfer chains

There are many case studies that examine separate components individually or viewing all systems as a single unit. A more comprehensive way is to explore multi-component systems as a chain which supplies or removes energy. This holistic approach can be found in the IEA Annex 49 [6] and in the advanced thermodynamic analysis developed by Tsatsaronis [7]. Due to the component interaction and interference this treatment not only reveals performance of a component but also refers to causes of the development of irreversibility.

The technological energy chain of building energy services begins with primary energy resources and ends with building service systems. A great deal of final energy consumption in buildings appears in HVAC technologies. In the last few decades, the attitude towards technological composition has shifted. Heating based on fuel combustion is inefficient and automated gas boilers have become a rather limited solution. Forms of energy – work and heat – participate in many transformative processes pertinent to this chain. These thermodynamic processes are typical of renewable energy transformers, cogeneration units, heat pumps, heat exchangers, energy accumulators, working fluid circulation pumps as well as control and adjustment equipment and others. Basically it is a system of various mechanical and energy transforming components. Over time, a wide range of processes and their changes, depending on the variable ambient temperature, should be objectively evaluated from the technological point of view using thermodynamic exergy analysis. The decomposition of this technological system into subsystems of chain allows the thermodynamic analysis to reveal and identify where the exergy is lost. The methodology and algorithms should be universal to the entire range of parameters in the energy chain assessment.

Observing the progress of exergy evaluation provides a few insights into different directions of evaluation methods and extends the potential of performance optimisation of buildings and their service systems.

1.2. Exergy efficiency

Exergy efficiency reveals the effectiveness or, on the other hand, the irreversibility of a process. The literature review shows that a different definition of this value is available. A good starting point when trying to define exergy efficiency is to define the incoming and outgoing exergy flows. This approach helps to expand the view and identify the spots of exergy destruction and, therefore, gain a better understanding if exergy losses can be reduced. Unfortunately there is lack of unified opinion on how to determine the amounts and directions of the flows and energy efficiency interpretations are still ambiguous.

According to the second law of thermodynamics the exergy efficiency boundaries are in the range of 0 and 1 due to fundamental mass-energy balance laws and the statement that entropy production are always equal or greater to 0. The results published by 8. Sakulpipatsin [8] may exceed these thermodynamic boundaries. When examined in the operational range, as done by Martinaitis and Streckienė [9], specific intervals highlight that efficiency values going below zero and becoming negative are an incorrect behaviour from the fundamental thermodynamics point of view. This fact illustrates the need to check expressions' behaviour in the used range or to clearly define the suitable application range.

The definitions of exergy efficiencies provided by several authors [7, 10, 11] have particular conditions which are impossible to satisfy at the same time. So, depending on various conditions, it is possible to define exergy efficiencies in various ways. It is stated that calculating exergy efficiency can be difficult due to the lack of solid standardisation and possible options for expression [11]. The authors follow the discussion on the definition of second law efficiency and suggest distinguishing two groups:

- Universal – ratio of all outgoing and ingoing exergy flows;
- Functional – ratio of the amount of the given (consumed) and generated (produced) exergy in a system [12].

As a result of universal and functional differences of efficiencies, separate expressions of efficiency should be used considering reference conditions.

The universal exergy efficiency is understood universally, but the intensity of system's changes has limited benefits of usage in exergy analysis. Functional exergy efficiency depends on the changes of the internal system configuration and has more benefits of usability, but it requires further specification of the system. It is stated that for certain systems appropriate specifications are difficult or quite impossible to formulate. In our article we are aiming to expand this perspective as well as the applicability of the method.

1.3. Reference temperature

Typically authors explore thermodynamic processes above or below reference temperatures. However, in some cases process flow temperatures in BSS can occur across the reference temperature during the year. This scenario has not been widely examined. Marmolejo-Correa and Gundersen [11] refer only to the work by Brodyansky et al [13], where some expressions under such operating conditions are given.

In exergy analysis the thermodynamic quality is determined in relation to the reference temperature (RT). Most authors accept this temperature as constant during the year.

With regards to the end-use part of energy transformation processes in HVAC technology, heat carrying fluid temperatures are at a relatively near-environmental temperature. Furthermore, the capacity variation depends on the environmental temperature. These systems have to deal with the variable reference temperature which can appear below, above and across operating temperatures of working fluids. It should be highlighted that it is difficult to find successful examples of calculations under these specific conditions. In the fore mentioned cases it is suggested to choose one [6] or more than one reference temperature representing a specific energy transformation technology by Meggers and Leibundgut [14] at a constant RT. Despite these suggestions, exergy efficiencies calculated according to the recommendations fail to fit within the boundaries of thermodynamic laws (0÷1) [8, 15]. There are solid complaints about procedures for determining exergy efficiency [11]. The aspects of the reference temperature variation are also discussed [10, 16, 17, 18]. Some of the suggestions how to deal with the stated problem of the variable RT going across fluid temperatures could be found by utilising the Carnot factor [9].

The method (calculation procedure) suggested in this paper aims at dealing with the problem of determining exergy efficiency when it is necessary to perform an exergy analysis for processes.

The processes at near-environmental conditions with a variable RT could be solved without restrictions in all possible cases when RT appears below, above and across the operating temperatures of working fluids. A ventilation heat recovery exchanger (HRE) was selected for this case study. This approach is suitable for the integration into simulation programs or manual calculations and can also be used for overall energy chain assessment.

2. Methodology

The main tasks of the exergy analysis (when exergy flows and efficiency have to be determined) are examined in a wide range of reference environment temperatures (e.g. from +30ºC to –30ºC) when it goes from above to below heat flow temperatures (e.g. from +5ºC to +22ºC). Despite the aforementioned case study temperature, the universal method is demonstrated. The methodical foundations of the assessment framework are explained in following subsections.

2.1. Potential of exergy flows

It is important to highlight that heat and exergy flows should not be treated equally. In order to solve this type of problem the following assumptions should be discussed and stated.

Given conditions should be defined: (a) the direction of thermal exergy is always directed towards the reference temperature, (b) the state parameters to define the potential of exergy flow should be selected.

Table 1

Expressions used for parameters of medium and reference environment

Temperature, K	Enthalpy, kJ/kg	Entropy, kJ/kgK	Coenthalpy, kJ/kg
Medium *i-th* state parameters			
T_i	$h_i = c_p T_i$	$S_i = c_p ln \frac{T_i}{273.15}$	$k_i = c_p \left(T_i - T_e ln \frac{T_i}{273.15} \right)^*$
Reference environment state parameters			
T_e	$h_e = c_p T_e$	$S_e = c_p ln \frac{T_e}{273.15}$	$k_e = T_e c_p \left(1 - ln \frac{T_e}{273.15} \right)$

Notes: direct expression of equation (1) from temperature at *i*-th state.

Basically, when analysing heat transfer processes, the defining parameter is the temperature while pressure differences define mass transfer processes.

In order to assess these processes when they are analysed together, the thermodynamic property of enthalpy is used. *i*-th state parameters of the heat carrying fluid (or mass flow rate of the fluid) and reference environment (T_e) parameters are given in the Table 1.

And yet we have to start with discussing temperatures. In our illustrative example, the potential of the temperature between the medium temperatures of the heat recovery device and the environment temperature is limited. This temperature is the reference environment for the exergy analysis and as it is typical of building service systems, it always varies during the operation.

In exergy analysis, where the first and second laws of thermodynamics are combined, the exergy flow rate could be expressed as the coenthalpy (k) (thermodynamic state property) according to the notation of Borel [5, 19]. The coenthalpy is a derivative state parameter from the enthalpy (h) and the entropy (s), calculated according to the following expression:

$$k_i = h_i - T_e s_i \, . \tag{1}$$

Then specific exergy flows used in the exergy analysis for i-th flow are calculated:

$$e_i = k_i - k_e = \left(h_i - h_e\right) - T_e\left(s_i - s_e\right) . \tag{2}$$

The process which takes place from state „1“ to state „2“ could be defined as the difference of coenthalpies:

$$e_{12} = k_1 - k_2 = \left(h_1 - h_2\right) - T_e\left(s_1 - s_2\right) . \tag{3}$$

2.2. Direction of exergy flows

The principal scheme shown in Fig. 1 depicts the ventilation heat recovery exchanger. This case study is carried out under simplified conditions when the working fluid is dry air and the capacity (mass flow rates, M and heat capacities C_p) of hot (subscript h) and cold (subscript c) streams are equal to $\dot{M}_h c_{ph} = \dot{M}_c c_{pc}$.

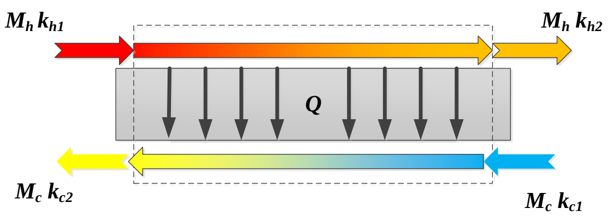


Fig. 1 The diagram of the exergy assessment for an air handling unit heat recovery device

Fig. 1 illustrates the hot and cold mas flow rates and the energy exchange between them via the heat flow (Q). Fig. 2 shows the cases when the variable reference temperature (RT) and flow temperatures with equal reference coenthalpy (RC) have a constant heat flow between heat carrying fluids and flow directions. In these charts (Fig. 2) the change of the flow temperature and coenthalpy content is expressed as the ratio of the transferred heat until the specific point (Q_i) and overall transferred heat in heat exchanger (Q_F).

Heat recovery temperature efficiencies of heat recovery exchangers for ventilation units are used:

$$\varepsilon_T = \frac{T_{h1} - T_{h2}}{T_{h1} - T_{c1}} \, . \tag{4}$$

The reference environment temperature is expressed in a manner of non-dimensional temperature which is calculated:

$$\bar{T}_e = \frac{T_e - T_{c1}}{T_{h1} - T_{c1}} \, . \tag{5}$$

In the paper we discuss the case of a heat recovery exchanger (HRE) at which boundaries of a given state should be assumed. The temperatures of the fluid remain constant and there is a steady state process ongoing in the HRE between hot and cold mass flows. A linear temperature change is assumed in order to simplify the case for demonstrational purposes. Ambient temperature is assumed to be variable and changing in the range which covers values below and above operational temperatures in the HRE. Table 2 summarizes parameters used in the study: temperatures and heat recovery efficiencies used to characterise the HRE performance:

Table 2

Medium temperatures and parameters of analysed cases

Position	T_{h1}	T_{h2}	T_{c1}	T_{c2}
Temperatures of the medium, °C	22	16,9	5	10,1

The following explanation covers the case shown in Fig. 2 in which the ambient temperature (that is used as the reference state for exergy analysis) varies in the range from below 0°C (a, b) to across (c÷h) and above 25°C (*i*, *j*) operating medium temperatures.

In Fig. 2 both the coenthalpy (left side) and temperatures (right side) of a hot and cold mass flow are given at the variable reference temperature (RT). RT is marked with the black line in the pictures on the right side. The other two lines show source fluid (red) which heats up the colder load fluid (blue). The coenthalpy changes of hot or cold fluids are bolded if exergy is consumed. Vertical dashed lines mark important points where state parameter lines intersect or change direction. In the pictures on the right, the horizontal dashed line shows the reference coenthalpy (RC) k_e.

We start with the example where the ambient temperature is below operating medium temperatures (a, b in Fig. 2). The rule of thumb is that a flow with a higher amount of coenthalpy transfers it to the flow with a lower value when the amount of coenthalpy is reduced in a parallel direction to the heat carrier flow. When the ambient (reference) temperature increases, this flow supplies the exergy to the point where they become equal (c, d in Fig. 2). From that point on (when the ambient temperature reaches this relation to the temperatures of flow) all exergy given to the device is destroyed. As ambient temperature rises further in different places, both hot and cold streams of fluid receive and return the exergy. This means that the same stream changes the status of the exergy transfer across the heat exchanger (e, f in Fig. 2). As previously mentioned, the stream with the higher coenthalpy supplies the exergy. This enables the increase and decrease of exergy content in the flow across the HRE (g, h in Fig. 2). The destruction of the consumed exergy during the rise of ambient temperature ends when the coenthalpy of the receiving flow starts to increase. From this point on, a further increase of ambient temperature influences the cold flow and supplies the exergy to the hot flow (i, j in Fig. 2).

This means that from the perspective of exergy, the roles are reversed. It is important to mention that it is not right to align the direction of heat and exergy flows. This rule could be suggested in calculation procedures and when commenting on the process. Since these fluxes have different directions in some cases, it should be mentioned in each specific section of the case.

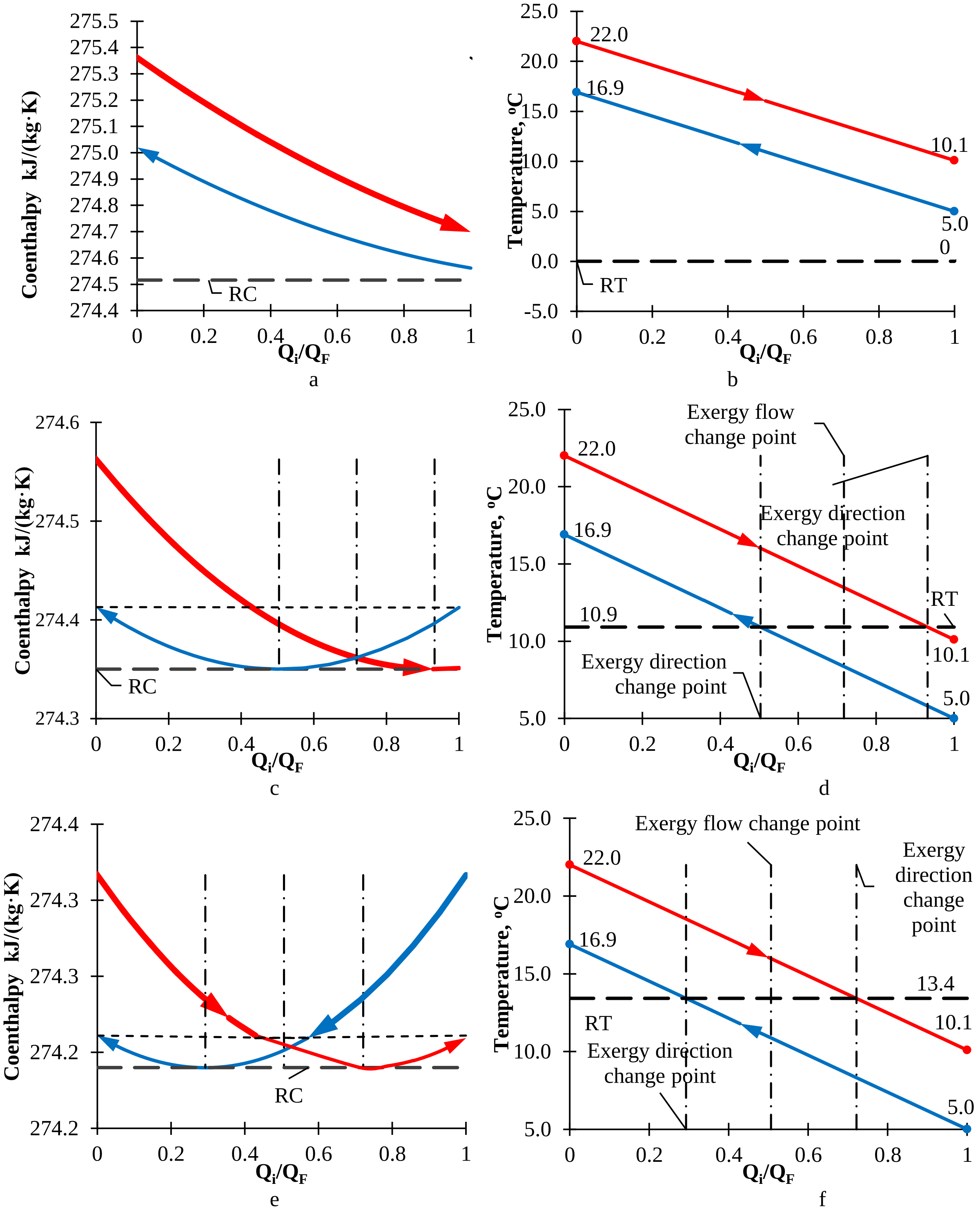


Fig. 2 Change of coenthalpy (a, c, e) and temperatures (b, d, f) across the heat exchanger at variable reference temperature ($\varepsilon_T = 0,7$). Group of (a, b) illustrates process above RC, (c, d) process condition 1, (e, f) process condition 2. Change of coenthalpy (g, i) and temperatures (h, j) across the heat exchanger at variable reference temperature ($\varepsilon_T = 0,7$). Group of (g, h) illustrates process condition 3, (i, j) - process below RT

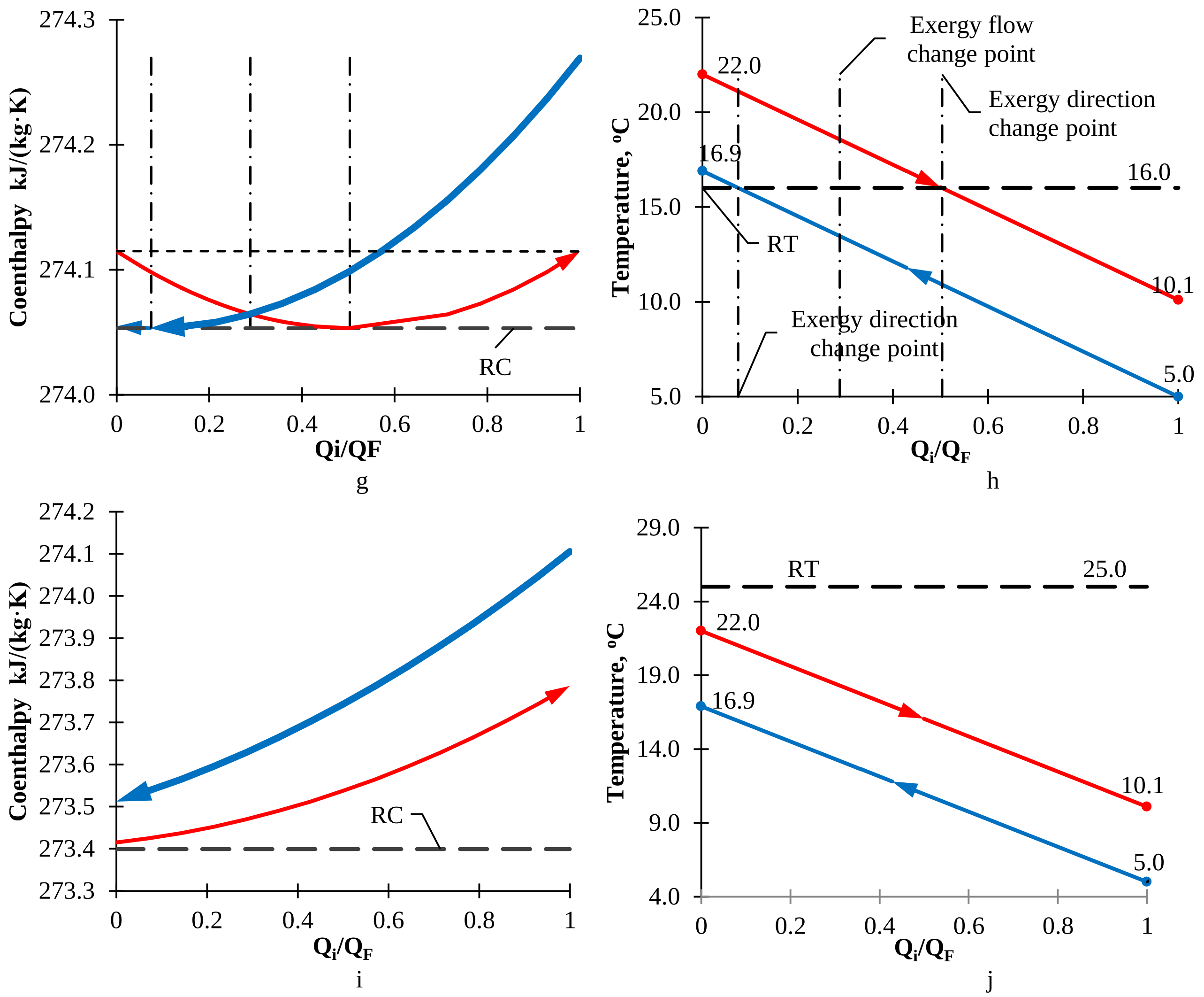


Fig. 2 Continuation

3. Results

The results of the presented research and the algorithm of calculation procedures could be summarized as the workflow of calculations.

It is much easier and reliable to examine mass and energy flows when variations are shown at suitable potential coordinates of pressures, temperature, enthalpy and entropy. When analysing exergy flows at coenthalpy coordinates, the interpretations in some cases might be unsuccessful due to the misleading evaluation of the direction of the exergy flow. It is quite typical in cases when the ambient temperature (which is used as the reference state) varies in the range above, across and below operating medium temperatures. As a reference parameter RC of the exergy analysis, coenthalpy k_e is always lower than (at specific cases it can also be equal to) any other enthalpy in the analysed examples in the process. If the operating temperatures of the medium are close to the environment, which is used as reference temperature, then k_e, as a minimum boundary, becomes less important. But when the variable reference temperature is placed across operating temperatures of working fluids, this behaviour becomes significant.

The amount of the exergy flow as a state parameter is determined as a difference of potentials or as a difference of coenthalpy. For exergy flows the rule stating that a higher coenthalpy transfers exergy to a coenthalpy with lower values should be applied. According to our assumptions, the reference coenthalpy k_e has the lowest values. This proposal could be extended with the assumption that if the flow of coenthalpy decreases, it releases exergy to the examined thermodynamic system. The opposite occurs when the coenthalpy increases, i.e. the flow absorbs exergy. These directions of exergy flows in this case are not related to mass flow inlets or outlets at the control volume boundary. An important thing to mention is that the direction of heat, mass and exergy flows should not be viewed as the same.

Our aim is to determine the exergy efficiencies of the process and produce a universal expression when the variable reference temperature (RT) is placed below, above and across operating temperatures of working fluids. In studies universal and functional efficiencies are usually used to express the effectiveness of a process [9]. The expression of functional and universal efficiencies by coenthalpy is as follows:

$$\eta_F = \frac{\dot{E}^-_{prod}}{\dot{E}^+_{consum}} = \frac{e^-_{prod}}{e^+_{consum}} = \frac{(k_{c2}-k_e)-(k_{c1}-k_e)}{(k_{h1}-k_e)-(k_{h1}-k_e)}. \tag{6}$$

An alternate formulation for functional efficiency is as follows:

$$\eta_F = \frac{(k_{c2} - k_{c1})}{(k_{h1} - k_{h2})}, \tag{7}$$

$$\eta_U = \frac{\dot{E}^-_{out}}{\dot{E}^+_{in}} = \frac{e^-_{out}}{e^+_{in}} = \frac{(k_{c2} - k_e) - (k_{h2} - k_e)}{(k_{c1} - k_e) - (k_{h1} - k_e)}, \tag{8}$$

$$\eta_U = \frac{k_{c2} + k_{h1} - 2k_e}{k_{c1} + k_{h1} - 2k_e}. \tag{9}$$

Despite the fact that numerical values of the universal (8) and the functional (6) exergy efficiencies are different, the performed analysis has shown that the created irreversibility (destroyed exergy) during the process remains constant in all cases:

$$l = e^+_{in} - e^-_{out} = e^+_{consum} - e^-_{prod} = (k_{h1} - k_{h2}) - (k_{c2} - k_{c1}). \tag{10}$$

When the destroyed exergy remains constant under all calculation conditions, efficiencies could be expressed when the main quantities of e^+_{in} and e^+_{consum} of exergy flows are used. By using these quantities functional and universal efficiencies could be expressed in the following way:

$$\eta_F = 1 - \frac{l}{e^+_{consum}} \ (11) \quad \text{and} \quad \eta_U = 1 - \frac{l}{e^+_{in}}. \tag{11}$$

It is important to mention that under the conditions when the reference environment temperature intersect flow temperatures, exergy flows should be taken into account in terms of direction. This aspect is highly important when it comes to calculating functional efficiency. Without assessing this aspect, expressions of efficiencies become negative. This result fails to satisfy thermodynamic laws without fitting within the range of 0÷1.

The previously mentioned expressions of incoming (for universal exergy efficiency) and consumed (for functional exergy efficiency) exergy expressions in described cases are shown in Table 2 and the algorithm sequence is depicted in the flow chart presented in Fig. 3.

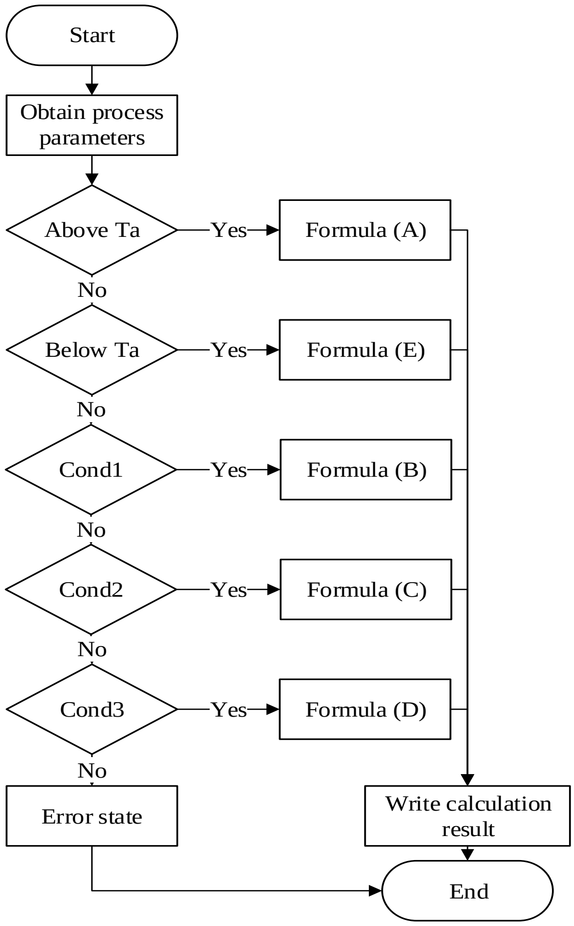


Fig. 3 Flow chart of calculation procedure

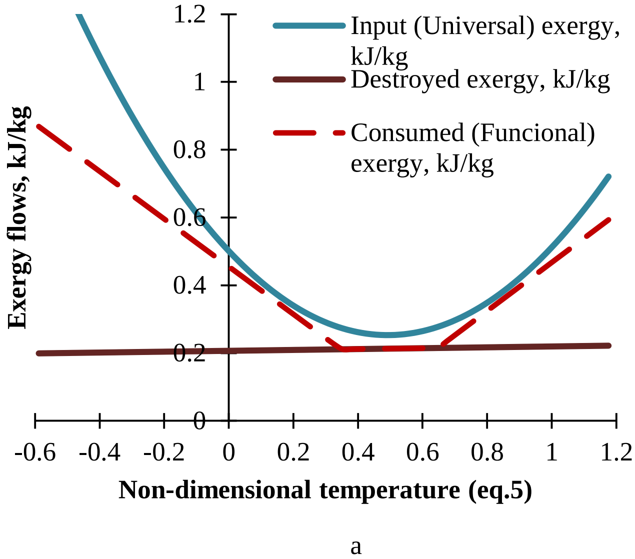
The depictions of heat recovery temperature efficiency 0.7 (Fig. 4) show the results of the calculations based on the methodology developed in this paper. The numerical value variation of the destroyed exergy l, incoming exergy e^+_{in} and consumed e^+_{consum} are presented on the left side. The numerical values of universal and functional exergy efficiencies are shown on the right side.

Table 3

Summary of exergy flow expression in coenthalpies

	Incoming exergy flow	Consumed exergy flow
	e^+_{in}	e^+_{consum}
(A)	$(k_{c1} - ke) - (k_{h1} - ke)$	$(k_{h1} - k_{h2})$
(B)	$(k_{c1} - ke) - (k_{h1} - ke)$	$(k_{h1} - k_{h2}) + (k_{c1} - k_{c2})$
(C)	$(k_{c1} - ke) - (k_{h1} - ke)$	$(k_{h1} - k_{h2}) + (k_{c1} - k_{c2})$
(D)	$(k_{c1} - ke) - (k_{h1} - ke)$	$(k_{h1} - k_{h2}) + (k_{c1} - k_{c2})$
(E)	$(k_{c1} - ke) - (k_{h1} - ke)$	$(k_{c1} - k_{c2})$

Values are given at variable reference temperature (RT) expressed by non-dimensional temperature (Eq. (5)). The sample of initial data values illustrates the range which is quite typical of a ventilation heat recovery exchanger. Boelman and colleagues [15] have created valuable methodical outcome of the HRE exergy analysis and the highlighted methodology gaps at variable reference (ambient) temperatures.



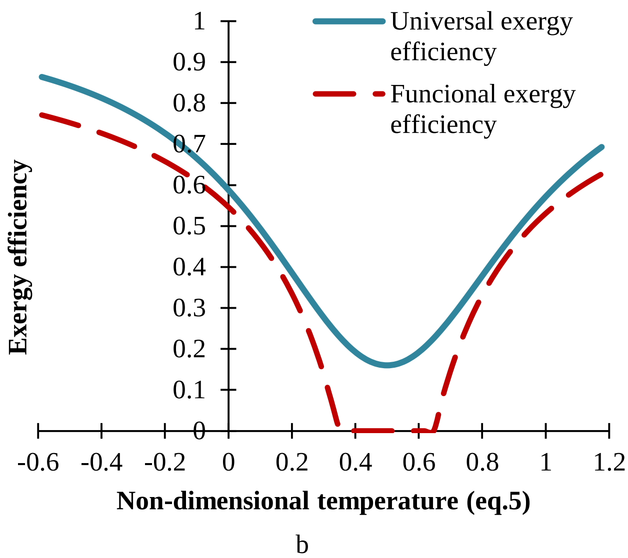


Fig. 4 Change of exergy flows (a) and exergy efficiencies (b) across the heat exchanger for variable reference temperature ($\varepsilon_T = 0{,}7$)

As shown in Fig. 5, the application of the proposed formula for functional exergy efficiency leads to results going below thermodynamic limits (0÷1). It is highly possible that this deviation has not been noticed due to limited possibilities of interpreting the exergy flow exchange across the fluid flow direction when reference temperature varies. By employing the co-enthalpy as a state parameter describing exergy flow, the method of HR exergy efficiency calculation becomes reasonable and correct.

It should be highlighted that defined functional efficiency is more sensitive to process changes than the universal one. The most important aspect is that result fits in in the boundaries of thermodynamic laws (0÷1) and destroyed exergy at all times remains positive.

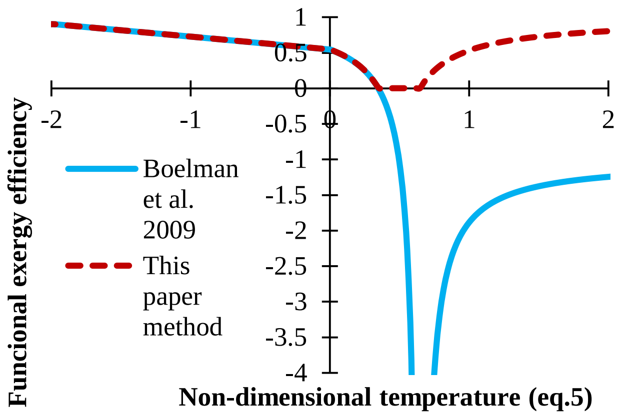


Fig. 5 Comparison of functional exergy efficiency calculation results

4. Conclusions

In this paper the thermodynamic state parameter coenthalpy is used as a direct exergy flow potential. The graphic interpretation of the changes of this parameter allow to unambiguously identify the direction of the exergy flow in the heat exchanger at a variable RT. The analytical description of this process has allowed developing a method of calculating exergy efficiency, in which the numerical results are consistent with the thermodynamic limit to 0 from 1.

The capabilities of this method are demonstrated in the case study of the exergy analysis of a ventilation heat recovery exchanger. Thermodynamically justified numerical values of the universal and functional exergy efficiencies for variable reference temperatures RT are shown. This approach is suitable for the operational range of HVAC systems when reference environment temperature is above, across and below temperatures of operating fluids.

The proposed method is distinguished by its universality and can be applied for other HVAC equipment. Results from this study could be useful for creating a designed optimised for exergy and ensuring efficient control of HVAC systems operating at variable reference temperatures as well as the examination of the efficiency of a seasonal energy transfer chain.

5. Acknowledgments

This research was funded by a grant (No. MIP-077/2015) from the Research Council of Lithuania. The authors would like to express their gratitude to reviewers for valuable feedback.

References

1. **Baehr, H. D**. 1962. Thermodynamik : Eine Einfuehrung in Die Grundlagen Und Ihre Technischen Anwendungen, Berlin/Göttingen/Heidelberg: Springer. http://dx.doi.org/10.1007/978-3-642-24161-1.
2. **Szargut, J. and Petela, R.** 1965. Egzergia, Wydawnictwa Naukowo-Techniczne, Warsaw.
3. **Szargut, J., Morris, D. R. and Steward, F. R**. 1988. Exergy Analysis of Thermal, Chemical and Metallurgical Processes, Hemisphere Pub., New-York. 332 p.
4. **Bejan, A**. 1988. Advanced Engineering Thermodynamics, Wiley, New York. 758 p.
5. **Borel, L., Favrat, D.** 2010. Thermodynamique et Énergétique, Lausanne: Presses polytechniques romandes.

6. IEA ECBCS Annex 49. 2010. Low Exergy Systems for High-Performance Buildings and Communities.
7. **Tsatsaronis G. Morosuk T.** 2012. Advanced thermodynamic (exergetic) analysis, Journal of Physics Conference Series 395(1): 2160. http://dx.doi.org/10.1088/1742-6596/395/1/012160.
8. **Sakulpipatsin, P., van der Kooi, H. J., Itard, L. C. M. and Boelman, E. C.** 2008. The influence of possible definitions of a reference environment to determine the exergy of air in buildings, Int. J. Exergy 5(3): 275–295. http://dx.doi.org/ 10.1504/IJEX.2008.018111.
9. **Martinaitis V. Streckienė G.** 2016. Concerning exergy efficiency evaluation of heat recovery exchangers for air handling units. Int. J. Exergy. 381–404. http://dx.doi.org/10.1504/IJEX.2016.077432.
10. **Hepbasli A.** 2012. Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies, Renew. Sustain. Energy Rev 16: 73–104. http://dx.doi.org/10.1016/j.rser.2011.07.138.
11. **Marmolejo-Correa D. Gundersen T.** 2012. A comparison of exergy efficiency definitions with focus on low temperature processes. Energy Journal 44(1): 477–489. http://dx.doi.org/ 10.1016/j.energy.2012.06.001.
12. **Kotas T.J.** 1995. The Exergy Method of Thermal Plant Analysis, Krieger Publishing Company Malbar, Florida USA. 320 p.
13. **Brodyansky VM, Sorin MV, Le Goff P.** 1994. The efficiency of industrial processes: exergy analysis and optimization. Amsterdam: Elsevier. 512 p. http://dx.oi.org/10.1504/IJEX.2008.018111.
14. **Meggers F. M. and Leibundgut H.** 2012. The reference environment: Utilising exergy and anergy for buildings. Int. J. Exergy 11(4): 423–438. http://dx.doi.org/ 10.1504/IJEX.2012.050254.
15. **Boelman, E.C., Itard, L.C.M., Sakulpipatsin, P., Luscuere, P. G., and Van Der Kooi, H.J.** 2009. Functional exergy efficiency at near-environmental temperatures, ASHRAE Transactions 115: 748–759. http://dx.doi.org/10.1504/IJEX.2008.020827.
16. **Torio, H., Angelotti, A. and Schmidt, D.** 2009. Exergy analysis of renewable energy-based climatisation systems for buildings: A critical view, Energy and Buildings 41(3): 248–271. http://dx.doi.org/ 10.1016/j.enbuild.2008.10.006.
17. **Martinaitis V. Bieksa D. Miseviciute V.** 2010. Degree-days for the exergy analysis of buildings. Energy and Buildings 42(7): 1063–1069. http://dx.doi.org/ 10.1016/j.enbuild.2010.01.019.
18. **Pons M.** 2010. On the reference state for exergy when ambient temperature fluctuates. International Journal of Thermodynamics 12(3): 113–121. http://dx.doi.org/10.5541/ijot.246.
19. **Borel, L. and Favrat, D.** 2010. Thermodynamics and Energetics for Engineers, EPFL Press, Switzerland. 795p.

V. Martinaitis, J. Bielskus, K. Januševičius, P. Bareika

EXERGY EFFICIENCY OF A VENTILATION HEAT RECOVERY EXCHANGER AT A VARIABLE REFERENCE TEMPERATURE

S u m m a r y

The purpose of this paper is to develop the application of exergy analysis for assessing the performance of building mechanical systems. When exergy analysis is applied to thermal processes in HVAC systems, this method faces the conditions when variable reference temperature is placed below, above and across the operating temperatures of working fluids. Using the derivative status parameter from enthalpy and entropy, the methodology for calculating the exergy efficiency for HVAC equipment is proposed. The capabilities of this method are demonstrated in the case study of exergy analysis of a ventilation heat recovery exchanger. Thermodynamically justified numerical values of the universal and functional exergy efficiencies for variable reference temperatures are shown.

The proposed method is distinguished by its universality and can be applied on other HVAC equipment. Results from this study could be useful for creating exergy optimized design and developing efficient control of HVAC systems operating at variable reference temperatures.

Keywords: building mechanical systems; exergy efficiency; exergy analysis, ventilation air heat recovery exchanger.

Received October 12, 2016
Accepted February 06, 2017