

# ADVANCED THERMODYNAMICS METRICS FOR SUSTAINABILITY ASSESSMENTS OF OPEN ENGINEERING SYSTEMS

by

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Original scientific paper

UDC: 66.012

BIBLID: 0354-9836, 10 (2006) 1, 125-140

*This paper offers a verification of the following hypotheses. Advanced thermodynamics metrics based on entropy generation assessments indicate the level of sustainability of transient open systems, such as in manufacturing or process industries. The indicator of sustainability may be related to particular property uniformity during materials processing. In such a case, the property uniformity would indicate systems' distance from equilibrium, i. e., from the sustainable energy utilization level. This idea is applied to a selected state-of-the-art manufacturing process. The system under consideration involves thermal processing of complex aluminum structures during controlled atmosphere brazing for a near-net-shape mass production of compact heat exchangers.*

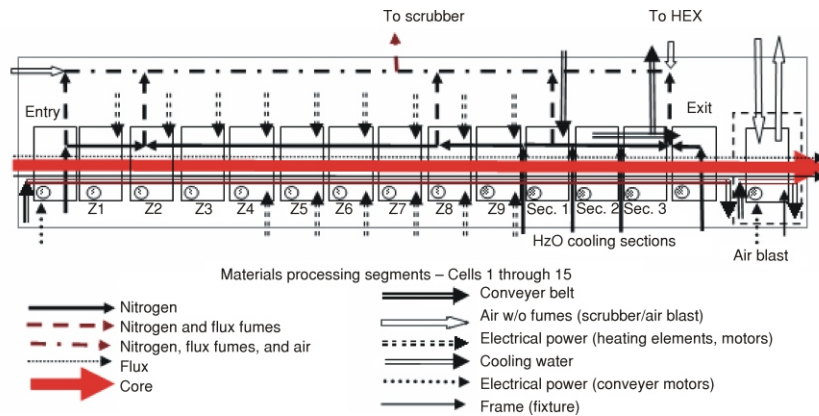
Key words: *thermodynamics metrics, manufacturing, sustainability*

## Introduction

Traditional tools of engineering thermodynamics, developed for analysis of energy resources utilization, have been exploited extensively and for a long time for improvements of complex engineering systems [1]. An ultimate objective of these systems is most often to secure an efficient energy use/delivery for a given task [2-4]. A large body of this knowledge has been developed for studies of closed, steady-state or quasi-steady-state systems, such as for large energy systems [5]. Among various analysis techniques developed, the most prominent have been various thermodynamics irreversibility assessment approaches, in particular exergy (*i. e.*, availability) [6, 7], and/or entropy generation methods [8]. Somewhat less prominently, these approaches have been used to analyze systems in which energy conversion is not the ultimate objective of the process *per se*. Instead, materials' modifications are the main focus of interest. Among these, manufacturing processes were rarely considered, except possibly for large metallurgical and/or petrochemical systems [9]. The lack of such studies is present especially for continuous manufacturing systems related to advanced materials processing, such as for a variety of non-traditional manufacturing technologies (*e. g.*, continuous and/or rapid solidification technologies), additive processes (for example, cold or thermal spray

technologies), and/or net-shape manufacturing (such as joining operations). A logical explanation for this inconsistency would be that, although energy intensity of these processes may be very high, the overall level of energy resources utilization may be rather low (compared to, say, modern energy systems). In addition, the main objective of such processes involves product quantity and its quality, not necessarily energy intensity. A given state-of-the-art materials processing technique was often taken as granted, regardless of resources utilization level or an eventual non-favorable sustainability level. However, a need to perform analyses of resources utilization, environmental, and societal impacts becomes more prominent with an increased awareness of the importance of sustainability assessments across all facets of societal development [10], in particular within the context of green engineering [11]. In addition, the large-volume manufacturing operations increasingly shift importance of such studies toward less traditional fields. For example, some of the state-of-the-art manufacturing technologies, historically focused primarily on an ultimate goal for a high product quality, *i. e.*, regardless of resources utilization and/or impact on the surroundings, now appear to be notoriously energy inefficient and often environmentally very unfriendly [12]. These systems (and the related processes) are, as a rule, open and transient (for example, joining technologies, such as mass production brazing in automotive industry, fig. 1, or soldering in electronics industry).

This paper is devoted to an illustration of the plausibility of using advanced thermodynamics for sustainability assessments of continuous manufacturing systems. The systems involved may feature a series of transient materials processing segments. The system under consideration will be a near-net-shape mass production of compact heat exchangers, *i. e.*, a controlled atmosphere brazing (CAB) furnace, fig. 1.

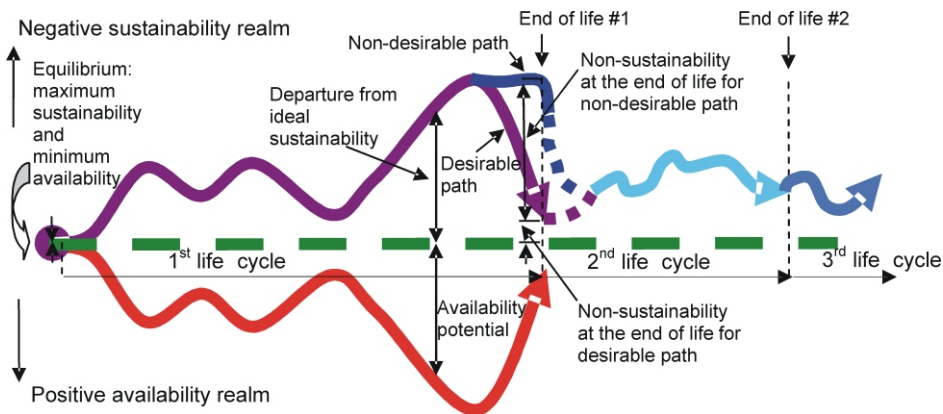


**Figure 1. A typical continuous (open) manufacturing system: a controlled atmosphere brazing processing in automotive industry [12]. The principal material flow is a discrete flow of heat exchanger cores through the sequence of heating/cooling zones. Various material/energy flows are being exposed to state/form change along the product flow path**

### Energy availability and sustainability levels

Mass, energy, and exergy balancing are not restricted only to steady or quasi-steady and closed systems. There is certainly no a fundamental problem in using these tools for continuous, transient and often variable-mass manufacturing systems/processes. In particular, the second law of thermodynamics methods (such as the ones developed in thermoeconomics [22]) are of interest. Multiple benefits of using such assessments may be identified [23]. These advantages stem, among other arguments, from the following two basic features of entities to be balanced: (1) the uniqueness of the definition of such a property for various process interactions/outcomes allows its applicability for an analysis of different segments of the processing, and (2) the additivity of extensive thermodynamics properties allows a material flow to be followed throughout its entire life cycle. These features – in conjunction with balancing rules for both conserved (energy) and non-conserved (exergy) flows – lead to specific resources metrics’ definitions, valid across boundaries of all the subsystems’ control volumes, encompassing even separate processing steps.

Therefore, such analysis tools may be applicable across diverse materials processing operations, such as machining, thermal treatment, forming, diffusion and phase change processing, *etc.* In a word, the techniques developed for closed and steady (or quasi-steady state) energy systems may be utilized to study open, transient manufacturing systems – along any segment of a material flow throughout the product’s life cycle, fig. 2.



**Figure 2.** A symbolic representation of a material flow path during processing: from an ideal sustainability state to a final state, along a multiple life cycle sequence. The negative sustainability realm corresponds to a finite departure from equilibrium – it is inherent to any creation of availability in the real world. The trade-off between the need to create availability and to preserve sustainability can be measured by entropy production. If the end of life reaches equilibrium with the environment for any material flow (being equal to the initial state of the material in the environment), an open system of a processing becomes a closed system

An idea of using advanced thermodynamics approaches to study non-energy systems (in particular in the chemical industry and related to environmental issues) is not new [13], but very little has been offered for manufacturing systems' sustainability assessments in general. What may encourage such assessments is the idea that a change of a property of a material under processing in any open manufacturing system (considered as an engineering setting of materials' processing anywhere along the path of the single/multiple life cycle), contributes to a certain degree to an overall outcome of all the interactions between material flows and surroundings, but considered as a closed system. This interpretation rests on the fact that each material flow would have/reach equilibrium with its surroundings, both at the site of its extraction from the surroundings, and upon its ultimate return to the environment for a full sustainability. Therefore, such a path would be possible to consider as a virtually closed cycle. It is important to note that, in energy terms, a departure from a desired sustainability, as a rule, means an increase in a potential availability of an energy resource, and *vice versa*.

Any sustainability approach struggles with a task to identify how far from equilibrium (*vs.* surroundings) a process and/or its outcomes are at any instant of the life cycle. By definition, the exergy and/or entropy generation approaches identify the points of equilibrium *vs.* relevant surroundings as the points where the involved driving potentials (availability) diminish (an equilibrium would constitute, in terms of sustainability, a desired but never achieved goal, but in terms of potential energy resources it represents, in a limit, a total loss of their *in situ* availability). Hence, each material flow that participates in a product formation of a manufacturing process starts its journey along the materials processing path from the point of equilibrium with the surroundings, where the exergy must be zero, and, when we finish watching processing to go "through its tricks, and calculate the number again" it (ideally) becomes the same as it was at the beginning, *i. e.* zero. A bit more subtle consequence of this behavior is that an open manufacturing process, if the boundaries of the system are extended to include the whole life cycle of a product, becomes a segment of a rigorously defined closed cycle, fig. 2.

### System description

A manufacturing system should be defined, as is customary for any thermodynamic system, as a physical entity of a complex structure that consists of a finite set of constitutive elements having: (1) a known type of each constituent, (2) defined internal constraints that control interactions between the constituents, (3) a known nature of internal forces, and (4) explicitly listed generalized coordinates that describe all actions of external forces [14]. This rigorous definition differs from a descriptive notion of a manufacturing system ("a complex arrangement of physical elements characterized by measurable parameters," as traditionally considered in manufacturing disciplines [24]). Consequently, any analysis of sustainability metrics of manufacturing systems must involve such an *a priori* defined system. In any such case, the system boundaries would be crossed by material flows and energy interactions, as is true for all other engineering systems if considered in the thermodynamics' realm.

The system under consideration is presented schematically in fig. 1 [12]. This system features a series of subsystems – heating/cooling zones. Within each such zone, all bulk material flows pass through, while being exposed to a certain materials' processing. For simplicity, within the considered system (*i. e.*, a continuous controlled brazing furnace), the material processing is reduced to both heating and/or cooling of a steady stream of products, *e. g.*, geometrically and structurally complex objects to be brazed (*i. e.*, the heat exchanger units). This processing is accomplished by heat interactions (radiation and convection heating and cooling). In addition, the process is accomplished under a controlled atmosphere. The bulk nitrogen flows, water and air streams interact with the products' material stream along the given sequence of sub-system zones. Complex chemical reactions involve flux action, assisting selective materials' phase change through an assisted wetting and spreading of the molten filler metal. These processes lead to a generation of effluents, some of which may be harmful to the environment. Therefore, this manufacturing system does represent an open thermodynamic system, but with spatially and temporally variable states of each material flow, and with a sustainability footprint that must be controlled.

### **Energy and exergy flow diagrams and efficiencies**

If an analyst rigorously accounts for all energy interactions and substances' flows along the path of the principal material flow (in this example, the principal material flow is a discrete flow of aluminum heat exchanger cores consisting of hundreds of parts to be joined by a help of up to ten thousand brazed joints), both energy (Sankey) and exergy (Grassmann) diagrams may be constructed [15]. Such analysis was recently performed for a state-of-the-art CAB system [12], and the results are illustrated in fig. 3.

It is obvious that this system suffers from tremendous energy inefficiency. If an efficiency of energy utilization is defined as the energy used for achieving the net-shape effect only (*i. e.*, brazed joints formations) *vs.* the total energy needed to perform the required materials processing (*i. e.*, involving the heating of a discrete material flow of the brazed units from the environmental to the peak brazing temperature level), this energy efficiency magnitude would be within the single digit brackets! Moreover, if an analysis of the distribution of energy efficiencies along the processing path is performed [12], a dramatic variation of efficiency levels may be identified, fig. 4. Since this system involves only thermal processing, a most important feature of this processing would be the temperature non-uniformity of the products during processing.

A logical hypothesis would be that utilization of energy for a given materials processing in a manufacturing process must depend on the level of temperature non-uniformity (within the processed material) [19]. This realization would ultimately lead to an identification of a relationship between energy efficiency *and* product quality, a correlation not necessarily obvious at the first sight. Such a relationship can subsequently be used for defining an objective function for manufacturing system optimization, with sustainability as a criterion and quality as a constraint. This issue will be considered in the concluding section of this paper.

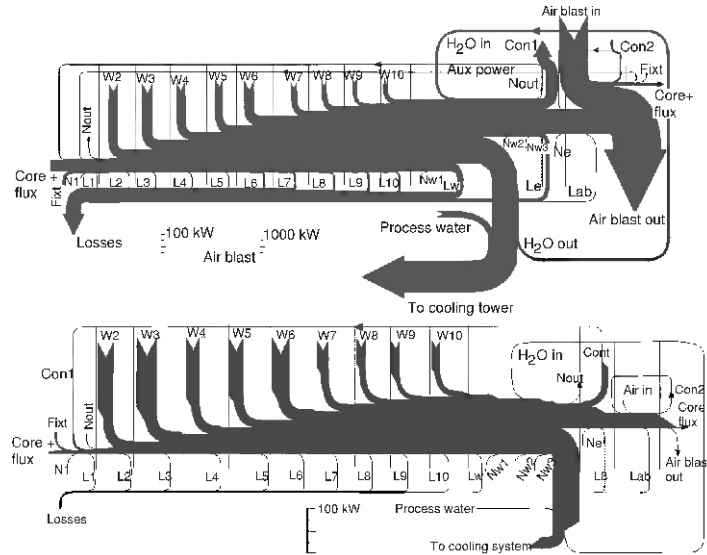


Figure 3. Sankey and Grassman diagrams of a system of fig. 1 [12]

In fig. 4, two figures of merit of energy utilization along the segments of the considered open system are presented (definitions of these figures of merit are included in the figure caption). The first is based on the first law of thermodynamics and the second one is based on both first and second laws of thermodynamics [16]. These are standard energy

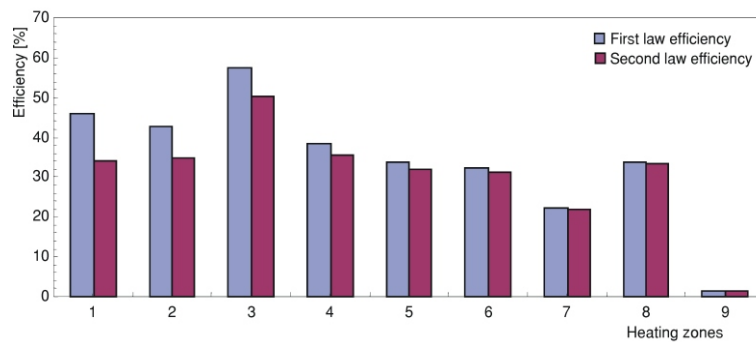


Figure 4. Distribution of first and second law of thermodynamics metrics for energy utilization and energy quality for the system in fig. 1. First law efficiency is defined as the ratio of the enthalpy rate change of the processed material vs. the energy input. Second law efficiency is defined as the first law efficiency multiplied by  $(1 - T_{ref}/T_{product}) / (1 - T_{ref}/T_{source})$ . Note that the entry zone, fig. 1, is not included in this plot

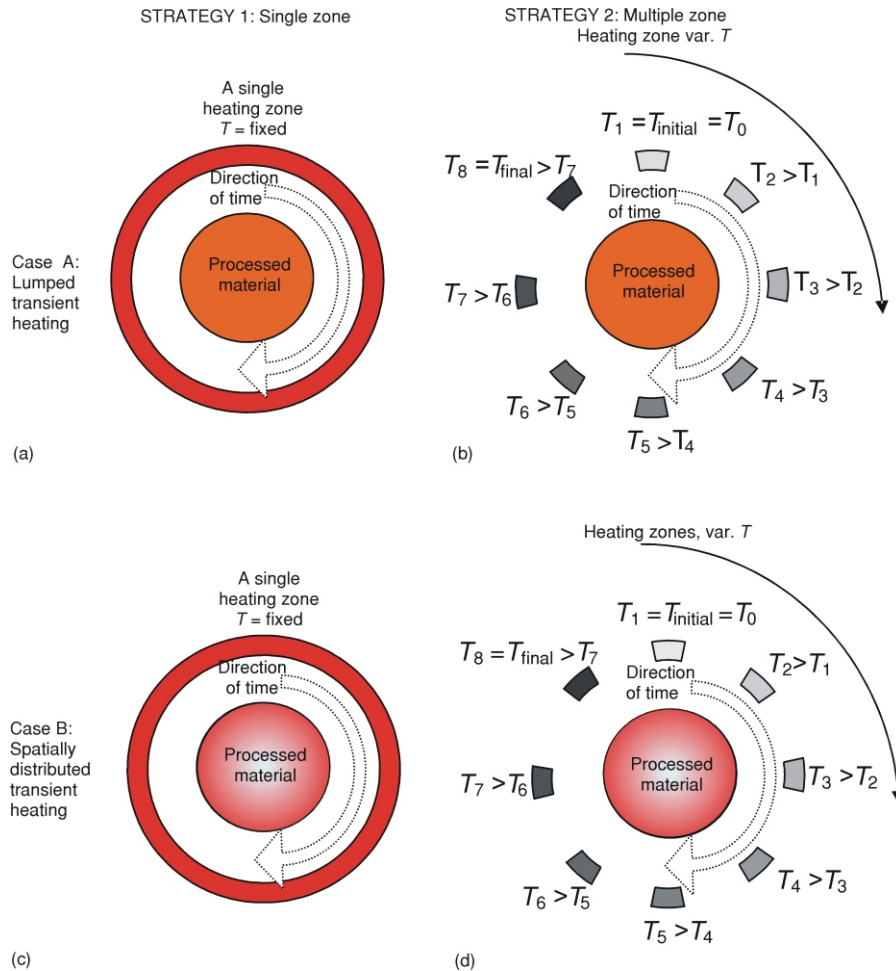
and exergy efficiencies, as defined by energy/exergy analysis [4], and have been used to describe energy utilization of a system exposed to a thermal interaction. These distributions are based on empirical (measured) values of energy demands for the brazing cycle of a system presented in fig. 1 [12]. It is interesting to notice that both efficiencies approach each other at higher temperature levels. This is due to a gradual decrease of temperature differences between the heating sources and processed material within each zone in the direction of the principal material flow. These temperature levels are carefully adjusted so as to achieve an imposed peak brazing temperature in a required processing time and within the imposed margin of temperature variations. Therefore, the presence of larger differences between the first and second law of thermodynamics efficiencies at all lower temperature zones *vs.* the values at the higher temperature zones leads to a realization that the quality of the available energy utilization *vs.* quantity is smaller during lower temperatures processing, but both the quantity and quality of energy use is still significantly inferior at high temperature levels. The key conclusion from this efficiency determination exercise is that both efficiencies may decrease dramatically at high temperature levels due to a significant decrease of the first law of thermodynamics efficiency anyway. The system under consideration represents a state-of-the-art process. However, to achieve the desired task (a uniform peak brazing temperature throughout the heat exchanger core), using a hypothetical ideal strategy involving such a process, a variable energy input would be needed for a unit of enthalpy change of the processed object (energy delivered locally at different zones of the process, with less utilized for the net-shape effect at the high temperature levels).

### Sustainability metrics and irreversibilities

To understand a bit better how the temperature uniformity affects utilization of energy during processing, let us consider its correlation with entropy generation. As is known [4], the Guoy-Stodola theorem [17] relates the loss of exergy to the entropy generation through a relationship as follows:  $\Delta \dot{E}x = T_{\text{ref}} \Delta \dot{S}_{\text{irr}}$ , where  $\Delta \dot{S}_{\text{irr}}$  represents the entropy generation (a non-property, *i. e.*, an additional production of entropy in excess to the entropy change  $\Delta \dot{S} = \dot{m} c \ln(T_{\text{final}} / T_{\text{initial}})$  manifested during product's change of state in an idealized reversible process, *i. e.*,  $\Delta T = 0$  within the product at an instant of time). Two cases and two heating strategies will be considered and compared to an actual situation, fig. 5.

Let us assume that an object exposed to processing (a heat exchanger core in the considered manufacturing process) is being heated from the given temperature to a peak processing temperature. The first situation, Case A, represents an idealized limiting case: a uniform temperature is kept throughout the material at any instant of time (but, the temperature changes with time). That is, the processed material is behaving as being exposed to a spatially lumped transient heating [18].

The second, Case B, represents a processing accomplished under an assumed finite thermal conductance to heat conduction within the material. The Case B is a much more realistic situation, *i. e.*, a transient heating of the object assumes a 2-D spatially dis-



**Figure 5. A symbolic representation of a simplified model of materials processing. Two cases correspond to a lumped (Case A), and to a spatially distributed (Case B) heating accomplished through two heating strategies, with either single (STRATEGY 1) or multiple (STRATEGY 2) heating zones**

*(a) lumped transient heating with a constant heating source temperature throughout (at any instant of time material has a uniform temperature); (b) the same as (a) but the heating is accomplished by using a series of heaters, each at a different, increasing temperature level; (c) spatially distributed heating with a constant heat source; (d) the same as (c) but with a series of heaters, each at a different, increasing temperature level*

tributed temperature within the material. This, in turn, inevitably leads to a presence of an inherent irreversibility of the heat conduction within the material, and to an existence of entropy generation.



In an actual situation, materials processing is conducted by radiation/convection heat transfer, exchanged between the processed material (*i. e.*, heat exchanger units) and heaters, in a transient manner and with all real 3-D features of this process that lead to the presence of significant temperature non-uniformities across the processed material, see fig. 8 later. This, actual, 3-D transient case will be denoted as Case C.

So, three models must be considered to calculate entropy generation for each case as follows:

$$S_{\text{gen}} = \Delta S_{\text{irr}} = \Delta S = \frac{dQ}{T_s} \quad (1)$$

where, for Case A (spatially lumped, transient – the least realistic):

$$Q = \rho V c (T_{\text{si}} - T_{\text{htr}}) \left[ 1 - \exp\left(-\frac{t}{\tau_t}\right) \right] \quad (2)$$

$$T_{\text{sf}} = T_{\text{htr}} + (T_{\text{si}} - T_{\text{htr}}) \exp\left(-\frac{t}{\tau_t}\right) \quad (3)$$

In eq. (2),  $Q$  is the energy transfer occurring up to the time  $t$  and it is idealized that this energy is transferred fully in form of heat, utilized for change of enthalpy of the heated object through an equivalent heat transfer (radiation/convection) mechanism described by an equivalent heat transfer coefficient  $h$ . Also, it is idealized that  $T_{\text{htr}}$  represents the relevant surroundings temperature for this heat transfer to take place, as traditionally adopted in any transient lumped heat transfer analysis [25].

For Case B (2-D spatial distribution, transient):

$$Q = \rho V c (T_{\text{si}} - T_{\text{htr}}) \left[ 1 - \frac{\sin \zeta_1}{\zeta_1} C_1 \exp\left(-\zeta_1^2 \frac{\alpha t}{L_c^2}\right) \right] \quad (4)$$

$$T_{\text{sf}} = T_{\text{htr}} + (T_{\text{si}} - T_{\text{htr}}) C_1 \exp\left(-\zeta_1^2 \frac{\alpha t}{L_c^2}\right) \cos \zeta_1 \quad (5)$$

One should be aware of a series of assumptions needed to interpret this simple 2-D transient model in the context of this analysis. In addition to a 2-D representation, this model assumes that equivalent energy transfer (radiation/convection) can be described in terms of corresponding equivalent Fourier and Biot numbers [25].

For Case C (actual 3-D, experimental data):

$$Q = Q \text{ (heating mode; process features)} \quad (6)$$

$$T_{\text{sf}} = T \text{ (material properties; process features)} \quad (7)$$

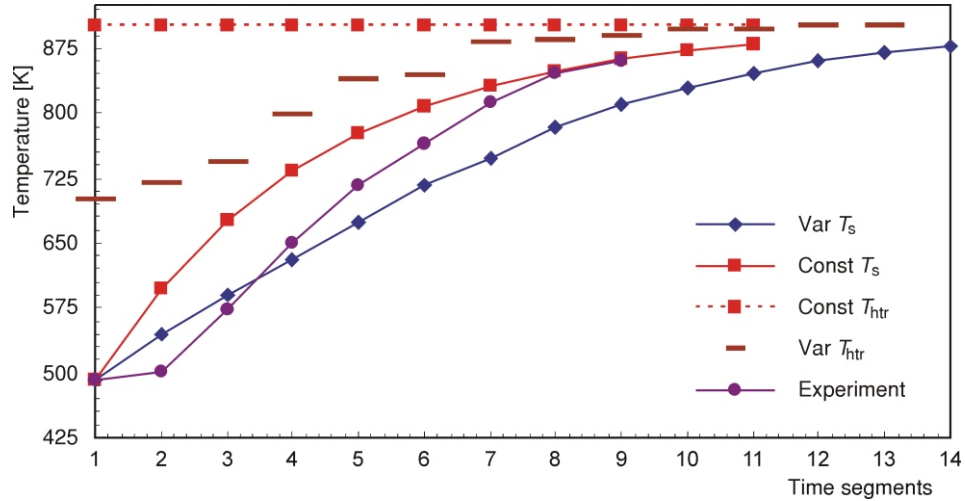
In either of the two idealized cases (A or B), the two heating strategies will be considered. The first one assumes a constant heating source temperature level, *i. e.*, during the entire heating (processing), the heat transfer rate is being delivered to the processed material from a given, high temperature level. The second heating strategy is accomplished in a more sophisticated manner. A number of temperature levels from a number of heaters along the time line of processing deliver the required heat transfer rate. In both heating strategies, the temperature differences under which the heat transfer rate is delivered from the heater temperature level to the surface of the material are being significantly reduced along the time line of heating. At the same time, the corresponding differences within the processed material in the first strategy (constant heating temperature) are, at first significantly larger than for the second strategy, but subsequently may become smaller due to a larger heating rate and, consequently, a shorter period of time. Why these strategies are selected needs to be clear.

In the second strategy, due to reduced temperature differences between the heater source and the material sink, at each instant of time for all early segments, the related entropy generation would be reduced (*vs.* the first strategy). For early time segments the temperature differences between the heater and the material are the largest. The consequences of the selected strategies, in turn, clearly demonstrate how the quality of energy utilization during processing may be enhanced with a more sophisticated heating strategy (and, in a final instance, improve sustainability of the product with respect to energy utilization, but keeping the product quality in an acceptable range). However, at higher temperature levels, a reversal in the quality of energy utilization is possible, and each case must be considered separately.

### **Irreversibility, product quality and processing strategies**

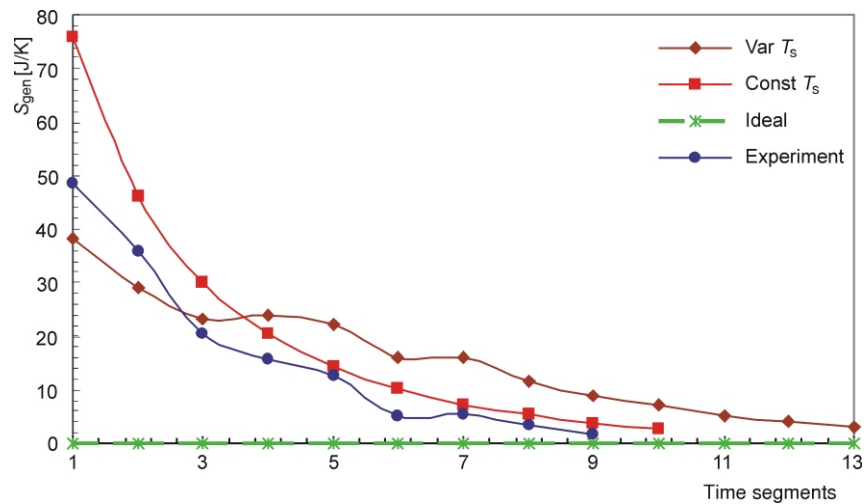
The comparison of entropy generation levels of Case A *vs.* Case B (*i. e.*, a lumped *vs.* a spatially distributed temperature changes within the manufactured object) should demonstrate that, in the idealized Case A, the entropy generation due to internal heat transfer evolution at an infinite speed of thermal equalization propagation leads to a negligible irreversibility (*i. e.*, zero entropy generation, that is, no temperature difference exists within the material). In a more realistic Case B (2-D spatial temperature distribution), thermal conduction within the material would evolve with a finite resistance, thus entropy generation would be different than zero. In that sense, the non-uniformity of a property (in this case temperature) indicates a departure from an ideal case, *i. e.*, from the energy utilization point of view the quality of the processing becomes inferior. At the same time, this non-uniformity is directly related to less than optimal brazing process conditions needed for making a good quality compact heat exchanger [19, 20].

Temperature behavior in three characteristic situations is presented in fig. 6 (heating only). For case A, the calculation leads to a zero entropy generation, see fig. 7. This is an expected result. Case A (fig. 5a, a lumped heat transfer process, *i. e.*, a uniform temperature distribution within a material at any instant of time) is, by definition, an ideal process that would ensure the best (in an idealized limit) quality of the final product – if



**Figure 6. Various temperature distributions. (1) Constant  $T_s$  and constant  $T_{htr}$ ; (2) Variable  $T_s$  and constant  $T_{htr}$ ; (3) Variable  $T_s$  and variable  $T_{htr}$ . For the sake of comparison, the actual material temperature distribution, the material was exposed to the same heaters distribution as for (3), is included as well**

the other brazing process parameters are achieved [21]. Case B (fig. 5c) corresponds to a more realistic situation; the entropy generation is finite, and its level indicates how far from the ideal processing an actual manufacturing outcome would be. If the second strategy is selected (fig. 5d), temperature differences between the material and the heater be-

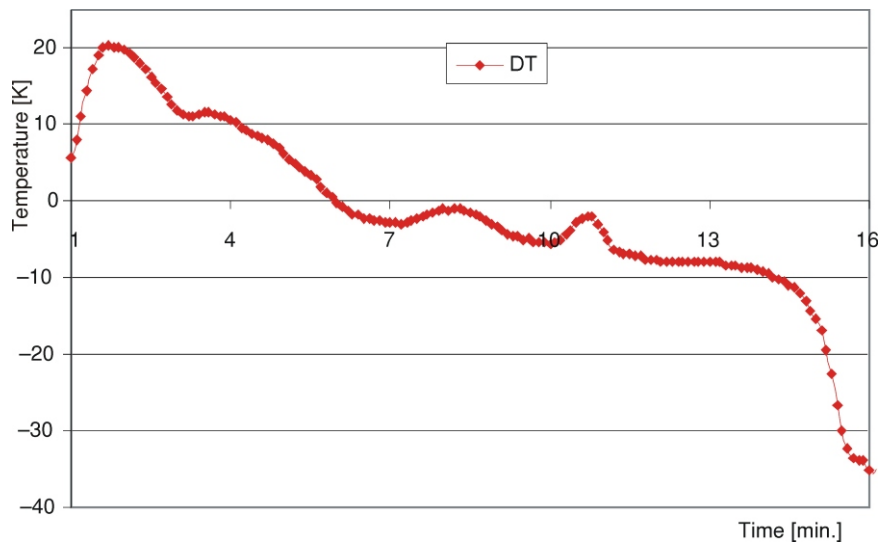


**Figure 7. Entropy generation for theoretical models (lumped case, 2-D spatially distributed transient – constant and variable heating sources), and experimental data**

come significantly smaller during initial stages of heating (temperature differences between the source and the material are inherently larger during initial stages vs. later stages).

For each case and/or strategy and/or the segment of heating, the corresponding entropy generation is calculated and presented in fig. 7 as a function of time. An expected result is obtained. The constant temperature heating source (*i. e.*, a single temperature level for the entire processing) leads to a distribution of entropy generation in time that features significantly larger irreversibilities at the beginning of the processing (due to significant corresponding temperature differences – source vs. sink *i. e.*, much larger than in the case of a set of variable temperature sources). That is a clear indicator that an eventual optimal distribution of sources may exist, even for the two idealized limiting situations, Case A (lumped transient), and Case B (2-D transient).

In fig. 7, the starting temperature of the processed material is 498 K, the temperature at the onset of brazing process after thermal degreasing (the early segments of materials processing, *i. e.*, before the Segment 1, are not included in the analysis). Experimental data for entropy generation for each heating segment are also presented in fig. 7. Theoretical calculations (for Cases A and B) assume the size and mass of the processed structure to be the same as for the actual brazed heat exchanger, but with equivalent properties, defined by considering the processed unit as a porous-like structure (*i. e.*, a fin/tube core of a high compactness), with an equivalent thermal conductivity and specific heat that take into account the actual object porosity.



**Figure 8. Temperature differences history across the processed material. The difference measured across the top surface diagonal of a heat exchanger unit during processing in a continuous controlled atmosphere brazing furnace**

An important additional aspect of the insight gained through accounting of entropy generation is worth emphasizing. An apparent indicator of the expected energy resources utilization deterioration (in terms of entropy production) is the processed material's inherent temperature non-uniformity. In real processing, as long as the conventional radiation and/or convection heating of the product as a whole is used, a presence of temperature non-uniformity within the material is inevitable.

In fig. 8, experimental data for the temperature difference across a core unit (between the diagonal corners of a rectangular core located at the top surface of the unit) during processing is compiled. The largest temperature differences before the onset of a quench (*i. e.*, for times less than 13 minutes) are within the first four zones, the same ones that feature the largest differences between the first and second law of thermodynamics efficiencies, and the largest entropy generation. The maximum allowed margin of 10 K (throughout the material heated) at the peak brazing temperature leads to an acceptable product quality, but requires a prolonged heating cycle. In any case, an optimization of temperature regimes through a selection of the heat sources distribution and corresponding temperature levels may clearly be performed, and should be utilized.

## Conclusions

Various scenarios may exist for performing a given manufacturing processing task. These scenarios are not equivalent as far as the energy utilization is concerned. The worst scenario for the energy utilization in the analyzed materials processing would be to keep a constant temperature of all the heating sources. In particular, this is the case at the initial time segments of the processing. Variability of temperature levels of the heating sources can reduce significantly the entropy generation (see initial time segments in fig. 7), but rigorous optimization of this distribution is a complex matter. In any case, an overall reduction of energy utilization may be achieved with different scenarios. It is interesting to note that data taken from an actual system indicate a poorer entropy generation status at the initial stages than obtained using a simplified model and a distribution of heat sources. At the later time segments of processing, the considered actual system seems to be well tuned.

The main purpose of this work has not been to establish an optimal distribution of temperature levels for a delivery of required heat transfer rates, but to demonstrate that entropy generation can provide a tool needed for identifying the energy utilization level quality, hence evaluating and important aspects of sustainability of a manufacturing system. A study of an environmental impact would be possible as well, through an identification of all effluent flows and through association of their exergy levels with any potential harmful effect.

An exergy deterioration of a material flow (identified either through the exergy balance or entropy generation calculation), may be related, at least in principle, to a monetary value of its rate. The particular relation between technical features of the processing and the monetary values of the losses may allow building of an objective function that

may be optimized in the same manner as it has been done for energy systems by using the tools of thermo-economics [22].

### Acknowledgments

An early version of this paper is presented by the first author as an invited lecture titled “Entropy-Based Metrics for Sustainability Assessments in Green Manufacturing” at the 2<sup>nd</sup> Int'l Conference on Green and Sustainable Chemistry and 9<sup>th</sup> Annual Green Chemistry and Engineering Conference, Washington DC, 2005, American Chemical Society. The research presented in the paper was funded by the Kentucky Science and Engineering Foundation through the grant KSEF-395-RDE-003. One of the authors (J. S.) acknowledges the Research Assistantship provided by the University of Kentucky Center for Manufacturing.

### Nomenclature

$A_s$	– surface area, [m <sup>2</sup> ]
$C_1$	– coefficient, [–]
$c$	– specific heat, [J/kgK]
$\Delta Ex$	– exergy flow rate, [kJ/s]
$h$	– heat transfer coefficient (effective), [W/m <sup>2</sup> K]
$L_c$	– ( $=V/A_s$ ), characteristic length, [m]
$m$	– mass of the core material, [kg]
$Q$	– heat energy delivered, [kJ]
$S_{gen}$	– entropy generated, $S_{irr}$ (not a property change), [J/K]
$S$	– entropy change, [J/kgK]
$t$	– time, [s]
$T_{htr}$	– heat source (surroundings) temperature, [K]
$T_{ref}$	– reference temperature, [K]
$T_{si}$	– core initial surface temperature, [K]
$T_{sf}$	– core final surface temperature, [K]
$V$	– volume of the heat exchanger core, [m <sup>3</sup> ]

### Greek letters

$\alpha$	– thermal diffusivity of the core material, [m <sup>2</sup> ]
$\rho$	– density of the core mass, [kg/m <sup>3</sup> ]
$\zeta_1$	– the first eigenvalue, [rad]
$\tau$	– ( $=\rho Vc/hA_s$ ), thermal time constant, [s]

### References

- [1] Bošnjaković, F., Technical Thermodynamics, Holt Reinhart and Winston, New York, USA, 1965 (6<sup>th</sup> German ed., *Technische Thermodynamik*, Steinkopf, Dresden, German DR, 1972)

- [2] Keenan, J. H., Availability and Irreversibility in Thermodynamics, *British J. of Applied Physics*, 2 (1951), pp. 183-192
- [3] Gaggioli, R. A., Principles for Thermodynamic Modeling and Analysis of Processes, *Proceedings*, ASME Advanced Energy Systems Division, AES – Vol. 36, ASME 1996, pp. 265-270
- [4] Bejan, A., *Advanced Engineering Thermodynamics*, John Willey and Sons, New York, USA, 1988
- [5] *Proceedings*, International Symposium on Efficiency, Costs, Optimization and Simulation of Energy Systems – ECOS 92 (Eds. A. Valero, G. Tsatsaronis), ASME, New York, USA, 1992
- [6] Rant, Z., Exergy, a New Term for Technical Work Availability (in German), *Forsch. Ing. Wes.*, 22 (1956), 1, pp. 36-37
- [7] Kotas, T. J., *The Exergy Method of Thermal Plant Analysis*, Butterworths, London, 1985
- [8] Bejan, A., *Entropy Generation through Heat and Fluid Flow*, John Willey and Sons, New York, USA, 1982
- [9] Szargut, J., Morris, D. R., Steward, F. R., *Exergy Analysis of Thermal, Chemical and Metallurgical Processes*, Hemisphere Publishing Corporation, New York, USA, 1988
- [10] Mihelcic, J. R., Crittenden, J. C., Small, M. J., Shonnard, D. R., Hokanson, D. R., Zhang, Q., Chen, H., Sorby, A., James, V. U., Sutherland, J. W., Schnoor, J. L., Sustainability Science and Engineering: The Emergence of a New Metadiscipline, *Environ. Sci. Technol.*, 37 (2003), pp. 5314-5324
- [11] Anastas, P. T., Heine, L. G., Williamson, T. C., *Green Engineering*, ACS Symposium Series 766, American Chemical Society, Washington, DC, 2001
- [12] Sankara, J., Sekulić, D. P., Irreversibility Approach for Sustainability Analysis of a Netshape Manufacturing System, *IMECE2004-61592*, 3, ASME, New York, USA, 2004
- [13] Bakshi, B. R., A Thermodynamic Framework for Ecologically Conscious Process Systems Engineering, *Computers and Chemical Engineering*, 26 (2002), 2, pp. 269-282
- [14] Gyftopoulos, E. P., Beretta, G. P., *Thermodynamics: Foundations and Applications*, Macmillan, New York, USA, 1991
- [15] Grassmann, von P., On a General Definition of the Figure of Merit (in German), *Chemie-Ingenieur-Technik*, 22 (1950), 4, pp. 77-80; 174
- [16] Moran, M. J., *Availability Analysis: a Guide to Efficient Energy Use*, Prentice Hall, Englewood Cliffs, NJ, USA, 1982
- [17] Kotas, T. J., Mayhew, Y. R., Raichura, R. C., Nomenclature for Exergy Analysis, *Proceedings, Inst. Mech. Engrs.*, Vol. 209, 1995, pp. 275-280
- [18] Mills, A., *Heat and Mass Transfer*, Irwin, Chicago, USA, 1995
- [19] Sekulić, D. P., Salazar, A. J., Gao, F., Rosen, J. S., Hutchins, H. F., Local Transient Behavior of a Compact Heat Exchanger Core During Brazing. Equivalent Zonal (EZ) Approach, *Int. J. of Heat Exchangers*, 4 (2003), 1, pp. 91-108
- [20] Shah, R. K., Sekulić, D. P., *Fundamentals of Heat Exchanger Design*, Wiley, Hoboken, NJ, 2003
- [21] Sekulić, D. P., Gao, F., Zhao, H., Zellmer, B., Qian, Y. Y., Prediction of the Fillet Mass and Topology of Aluminum Brazed Joints, *Welding Journal*, 83 (2004), pp. 102s-110s
- [22] Bejan, A., Tsatsaronis, G., Moran, M., *Thermal Design & Optimization*, John Willey and Sons, New York, USA, 1996
- [23] Sekulić, D. P., Entropy-Based Metrics for Sustainability Assessments in Green Manufacturing, 2<sup>nd</sup> International Conference on Green and Sustainable Chemistry, and 9<sup>th</sup> Annual Green Chemistry and Engineering Conference, Washington, DC, 2005  
<http://oasys2.confex.com/asc/green05/techprogram/index.html>.
- [24] Degarmo, E. P., Black, J. T., Kosher, R. A., *Materials and Processes in Manufacturing*, John Willey and Sons, New York, USA, 2003
- [25] Incropera, F. P., DeWitt, D. P., *Fundamentals of Heat and Mass Transfer*, John Willey and Sons, New York, USA, 2002

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Paper submitted: May 9, 2005  
Paper revised: January 12, 2006  
Paper accepted: February 13, 2006