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AN EVALUATION CRITICAL REVIEW OF THE MERIT OF AUGMENTATION TECHNIQUES BY SECOND LAW IN CIRCULAR TUBE WITH TWISTED TAPE AND WIRE COIL TURBULATORS

Assoc. Prof. Daniela Kostadinova, studing for PhD thesis
Department of Energy Techniques
Technical University of Gabrovo, 4 Hadzhi Dimitar Str.
5300 Gabrovo, Bulgaria
Phone: 0895419429
E-mail: didkamail78@abv.bg

Abstract: *There is an acknowledged growing need for efficient and sustainable systems that use available energy resources in an "optimal" (including constraints) way. Such a goal cannot be effectively achieved without taking into account the limits posed by the second law of thermodynamics A possible approach consists in the so-called entropy generation analysis, which possesses key features making it more attractive than traditional energy balance approaches. In fact, entropy generation analysis allows for a direct identification of the causes of inefficiency and opens up the possibility for designers to conceive globally more effective systems.*

This paper presents a critical review of contributions to the theory and application of entropy generation analysis to different types of tubes. The effects of insertion of the two turbulators with different coil pitch and twist ratios on heat transfer and friction loss in the tube are examined by the second law of thermodynamics. In this paper we use six different types of tubes with the coil pitch ratio (CR) and the twist ratio (Y) of twisted tape. The focus of the work is only on contributions oriented toward the use of entropy generation analysis as a tool for evaluation of combined twisted tape and wire coil.

Keywords: *Second law analysis, Entropy generation, Thermodynamic optimization, , twisted tape, wire-coil insert*

INTRODUCTION

Entropy generation minimization (finite time thermodynamics, or thermodynamic optimization) is the method that combines into simple models the most basic concepts of heat transfer, fluid mechanics, and thermodynamics. These simple models are used in the optimization of real (irreversible) devices and processes, subject to finite-size and finite-time constraints. The review traces the development and adoption of the method in several sectors of mainstream thermal engineering and science: cryogenics, heat transfer, education, storage systems, solar power plants, nuclear and fossil power plants, and refrigerators. Emphasis is placed on the fundamental and technological importance of the optimization method and its results, the pedagogical merits of the method, and the chronological development of the field.

Entropy generation minimization (EGM) is the method of modeling and optimization of real devices that owe their thermodynamic imperfection to heat transfer, mass transfer, and fluid flow irreversibilities. It is also known as ''thermodynamic optimization" in engineering, where it was first developed, or more recently as ''finite time thermodynamics" in the physics literature. The method combines from the start the most basic principles of thermodynamics, heat transfer, and fluid mechanics, and covers the interdisciplinary domain pictured in Fig. 1. The most exciting and promising interdisciplinary aspect of the method is that it also combines research interests from engineering and physics.

The objectives of the optimization work may differ from one application to the next, for example, minimization of entropy generation in heat exchangers, maximization of power output in power plants, maximization of an ecological benefit, and minimization of cost. Common in these applications is the use of models that feature rate processes (heat transfer, mass transfer, fluid flow), the finite sizes of actual devices, and the finite times or finite speeds of real processes. The optimization is then carried out subject tophysical (palpable, visible) constraints that are in fact re-sponsible for the irreversible operation of the device. The combined heat transfer and thermodynamics model ‘‘visualizes’’ for the analyst the irreversible nature of the device. From an educational standpoint, the optimization of such a model gives us a feel for the otherwise abstract concept of entropy generation, specifically where and how much of it is being generated, how it flows, and how it impacts thermodynamic performance.

The emergence of a new field of research is marked by the appearance of several fundamental results that hold for entire classes of known and future applications. Although isolated publications had appeared throughout the 1950s and 1960s, thermodynamic optimization emerged as a self-standing method and field in the 1970s in engineering, with applications notably in cryogenics, heat transfer engineering, solar energy conversion, and education. These first developments were reviewed in A. Bejan (1982), and A. Bejan (1996, 1982)

The field has experienced tremendous growth during the 1980s and 1990s. The objective of this article is to review the field, and to place its growth in perspective. The explosion of interest that we are witnessing today is due to three new developments: the diversification of the problems tackled in engineering after the energy policies of the 1970s, the lifting of the Iron Curtain and the absorption of work done by previously unrecognized pioneers, and the contributions that appear in the physics literature.

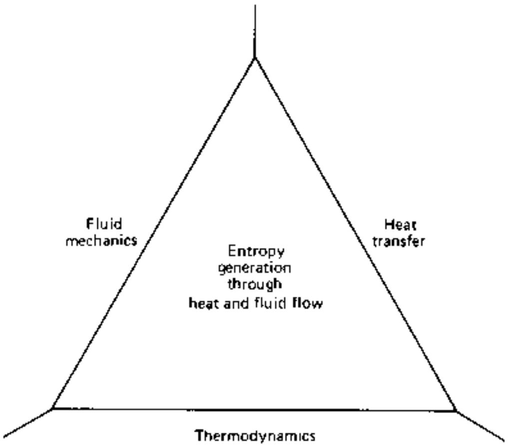

Fig. 1. The interdisciplinary field covered by the method of entropy generation minimization.

EXPOSITION

A solid thermodynamic basis to evaluate the merit of augmentation techniques by second law analysis has been proposed by Bejan (1982) in developing the entropy generation minimization (EGM) method which has been extended by Zimparov (2000, 2001a), including the effect of fluid temperature variation along the length of a tubular heat exchanger and assessing two objectives simultaneously. Following Bejan (1982), the thermodynamic impact of the augmentation technique is defined by the augmentation entropy generation number

$$N_{s,a} = \frac{\dot{S}_{gen,a}}{\dot{S}_{gen,s}} \qquad (1)$$

Augmentation techniques with Ns,a < 1 are thermodynamically advantageous since in addition to enhancing heat transfer, they reduce the degree of irreversibility of the apparatus. Ns,a can be rewritten (Bejan, 1982) as

$$N_{s,a} = \frac{N_T + \phi_o N_P}{1+\phi_o} \qquad (2)$$

If the heat flow is transferred at the wall boundary condition of constant heat flux, N_T and N_P can be presented (Zimparov, 2001a) in the forms

$$N_T = \frac{\left(\dot{S}_{gen,\Delta T}\right)_a}{\left(\dot{S}_{gen,\Delta T}\right)_s} = \frac{Q_*^2}{N_*^2 Nu_* L_*} \frac{T_{o,s}}{T_{o,a}} \tag{3}$$

where

$$\frac{T_{o,s}}{T_{o,a}} = \left[\frac{T_{i,s}}{T_{o,s}} + \frac{Q_*}{W_*}\left(1 - \frac{T_{i,s}}{T_{o,s}}\right)\right]^{-1} \tag{4}$$

and

$$N_P = \frac{\left(\dot{S}_{gen,\Delta P}\right)_a}{\left(\dot{S}_{gen,\Delta P}\right)_s} = \frac{W_*^3 L_*}{N_*^3 D_*^5} f_* = P_* \tag{5}$$

When the standard heat transfer passage is known, the numerical value of the irreversibility distribution ratio, $\phi_o = (\dot{S}_{gen,\Delta P} / \dot{S}_{gen,\Delta T})_s$ describes the thermodynamic mode in which the passage is meant to operate and can be presented (Zimparov, 2001a) in the form

$$\phi_o = \frac{f_s/2}{St_s}\left(\frac{T_i}{\Delta T}\right)_s^2 \left(\frac{u_m^2}{c_p T_i}\right)_s \frac{T_{o,s}}{T_{i,s}} \tag{6}$$

Case FG-1a

The case FG-1a seeks increased heat duty, $Q_* > 1$, or increased overall thermal conductivity $(UA)^* > 1$ and $N_{s,a} < 1$, for constant exchanger flow rate $W^* = 1$ and $G^* = 1$, $\mathrm{Re}_a = \mathrm{Re}_s$. Another constraint is fixed heat transfer area $D^* = 1$, $N^* = 1$, and $L^* = 1$.

$$(UA)_* = \frac{1 + \beta_s}{St_*^{-1}(f * P_*^{-1} A_*^{-2})^{1/3} + \beta A_*^{-1}} \tag{7}$$

$$P_* = f * A * G_*^3 \tag{8}$$

The pumping power of the augmented tube will increase, $P_* > 1$, due to the higher friction characteristic of the augmented surface. Equations (7) and (8) give

$$(UA)_* = \frac{1 + \beta_s}{St_*^{-1} + \beta} \tag{9}$$

and

$$P_* = 1 \tag{10}$$

$$Q_* = W_* \varepsilon_* \tag{11}$$

If the entering fluid temperatures are fixed, $\Delta T_i^* = 1$, Eq. (11) gives $Q_* = \varepsilon_*$. If $R_{ext} = 0$ and $\beta = \beta_s = 0$, Eq. (9) yields

$$(UA)_* = St_* \tag{12}$$

Equation (12) gives only the increase of overall thermal conductivity of the heat exchanger. For this case, the augmentation entropy generation number (Zimparov, 2001a) becomes

$$N_{s,a} = \frac{1}{1+\phi_o}\left(\frac{Q_*^2}{Nu_*}\frac{T_{o,s}}{T_{o,a}} + \phi_o \frac{f_*}{D_*^5}\right) \tag{13}$$

Figure 2 presents the variation of the augmentation entropy generation number $N_{s,a}$ and figure 3 the ratio $N_s^+ = N_{s,a}/Q_*$ .As seen, $N_{s,a} < 1$ and $N_s^+ < 1$ for all Reynolds numbers in the range. The variation of $N_{s,a}(Re)$ has a minimum for tube 04:04 at $\mathrm{Re} = 3.10^3$ and increases gradually for $\mathrm{Re} > 3.10^3$. The variation of ration N_s^+ has a similar behaviour, but with one and the same minimum at $\mathrm{Re} = 3.10^3$, the best flow regime.

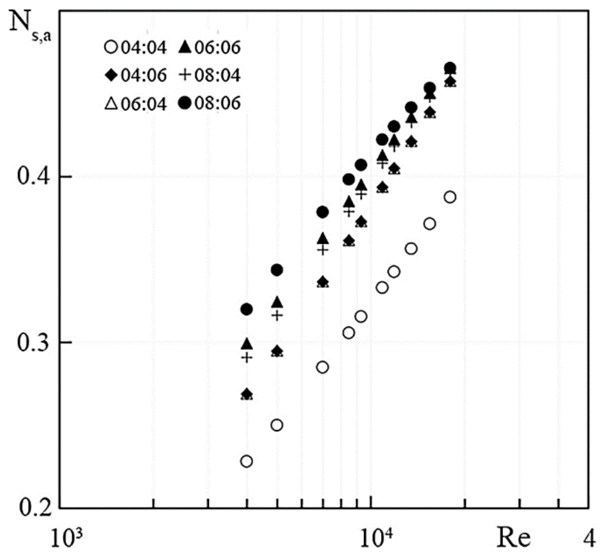

Fig. 2 Variation $N_{s,a}$ with Reynolds number (case FG-1a)

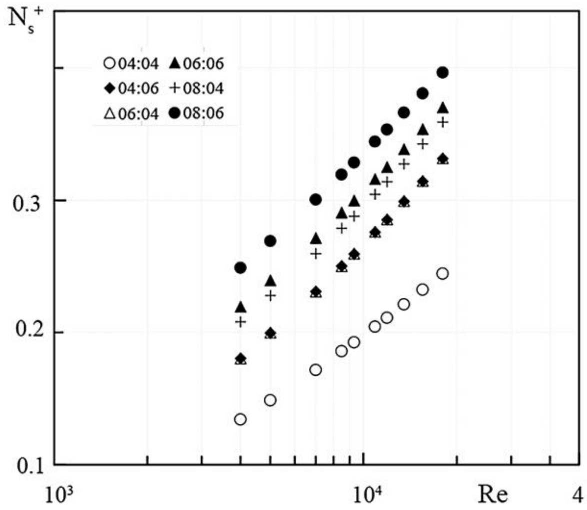

Fig. 3 Variation N_s^+ with Reynolds number (case FG-1a)

CONCLUSION

Several conclusions can be drawn from these results:

When the objective is increased heat flow, Q* > 1, the evaluation of the possible benefits must be fulfilled by use of criteria FG-1a, FG-2a, and VG-2a.

An enhanced heat transfer technique will be beneficial if the objective imposed by the 1st law, Q* > 1, is achieved, and simultaneously, the requirement for reduction of the entropy generation, Ns,a < 1, is also fulfilled.

An enhanced heat transfer technique will be beneficial if the objective imposed the optimum flow regime (range of Re with maximum benefit) in augmented tubes. It is achieved where the ratio N_s^+ has a minimum.

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