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FLOW EXERGY DESTRUCTION IN DUCTS

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Abstract: In this study, exergy destruction is studied theoretically in a methodological manner for flow systems. The equation of the rate of flow exergy destruction is derived beginning from the definition of exergy for forced convective flow through a duct. The second law of thermodynamics is applied on convective systems to investigate the irreversibilities which are the indicator of the destruction of available work named also as exergy destruction. Explicit form of exergy destruction equation for incompressible Newtonian fluid flow in two-dimensional Cartesian coordinates is presented as an example. A new term for dimensional quantitative results of flow exergy destruction, named *exergy destruction factor*, is also introduced. The study, being important for all academic researchers as well as engineers in efforts of research and development, will be helpful for understanding exergy destruction with the physics of incompressible transient laminar convection in ducts. The study addresses the fundamentals of thermodynamics.
Keywords: Exergy, Exergy destruction factor, Entropy generation, Laminar convection.

KANALLARDA AKIŞ EKSERJİ YIKIMI

Özet: Bu çalışmada, ekserji yıkımı akış sistemleri için teorik olarak metodolojik şekilde çalışılmaktadır. Akış ekserjisi yıkım hızı denklemi bir kanal boyunca zorlanmış taşınım için ekserjinin tanımından başlayarak türetilmektedir. Termodinamiğin ikinci yasası ekserji yıkımı olarak da adlandırılan kullanılabilir enerjinin kaybının belirtisi olan tersinmezlikleri araştırmak için taşınım sistemlerine uygulanır. İki boyutlu kartezyen koordinatlarda sıkıştırılamaz Newtonyen akışkan akışı için ekserji yıkımı denkleminin açık şekli örnek olarak sunulmaktadır. Akış ekserji yıkımının boyutlu sayısal sonuçları için *ekserji yıkım faktörü* adı verilen yeni bir terimde tanıtılmaktadır. Bütün akademik araştırmacılara olduğu kadar araştırma ve geliştirme çabasındaki mühendisler içinde önemli olan bu çalışma, kanallarda sıkıştırılamaz geçici laminer taşınımın fiziği ile ekserji yıkımının anlaşılabilmesinde yararlı olacaktır. Çalışma termodinamiğin temellerine hitap etmektedir.
Anahtar kelimeler: Ekserji, Ekserji yıkım faktörü, Entropi üretimi, Laminer taşınım.

NOMENCLATURE

A_R	aspect ratio (D/L)
Br	Brinkman number $Br = \dfrac{u_0^2 \mu}{k\ \Delta T}$
D	hydraulic diameter, [m]
$\dot{E}_x$	exergy [W/m3]
k	thermal conductivity, [W/m K]
L	length, m
Ma	Mach number
N_s	dimensionless entropy generation number
Pr	Prandtl number $\Pr = \dfrac{\nu}{\alpha}$
Re	Reynolds number $\mathrm{Re} = \dfrac{u_0 D}{\nu}$
$\dot{S}'''$	entropy, [W/m^{3}K]
T	temperature, [K]
u	dimensionless horizontal velocity component
v	dimensionless vertical velocity component
$\dot{W}_{lost}$	lost available work, [W/m^3]
x, y	dimensionless coordinates

Greek letters

α	thermal diffusivity, [m^2/s]
δ	cronecker delta δ_{ij}=1 for i=j and δ_{ij}=0 otherwise
ε	energy-scale of the molecules
γ	specific heat ratio (c_p /c_v)
ρ	dimensionless density
ν	kinematic viscosity, [m^2/s]
τ	dimensionless time
Φ	viscous dissipation function, [s^{-2}]
μ	dynamic viscosity, [N s/m^2]
Φ	irreversibility distribution function
Ω	dimensionless temperature difference

Subscribes

0	reference state, ambient
gen	generation
in	inlet
max	maximum
wall	wall
xd	exergy destruction
xdf	exergy destruction factor

INTRODUCTION

During last decades the investigation of exergy appears as an equivalent term of availability in Europe in 1950's and defined as the research of the maximum amount of work that can be produced by a system or a flow of matter or energy (Wylen et al. 1993, Bejan, 1979, Moran and Shapiro, 2004). Analysis of the exergy destruction is important in upgrading the energy utilization performance of thermal systems suffering from energy loses. Various applications including the stationary ducts can be found in the open literature. The engineering function of ducts is considered as the heat transfer between the walls and the flowing fluid. The quantities that affect the energy utilization performance of the convective flow are the heat transfer rate and irreversibility. The irreversibility is an indicator of the destruction of available work of the system and it is measured by exergy destruction; therefore, the second law analysis is applied to investigate exergy destruction rate.

In this study, the rate of flow exergy destruction is analyzed by spending effort to supply an easy method starting from thermodynamic analysis to the calculation of forced convective flow exergy destruction in ducts. The study addresses the fundamentals of thermodynamics and will be helpful for understanding the exergy destruction with the physics of forced convection. A new term for quantitative results of flow exergy destruction, named *exergy destruction factor*, is introduced. In the manuscript, the reader can find respectively that the derivation of equations of entropy generation and exergy destruction, definition of exergy destruction factor and an example which is considered to indicate explicit forms of governing equations in connection with the exergy destruction in a convective system modeled as transient and incompressible in two-dimensional parallel-plate ducts.

FUNDAMENTALS OF THE PROBLEM

EXERGY DESTRUCTION

In upgrading the system performances, the efficient energy utilization should be managed by quantitative controls of energy loses. The measure of energetic losses is treated as the existence of irreversibilities indicating the distinction between ideal and real processes. Exergy is a powerful concept supporting the efforts of energy lost investigations for energy system's enhancement. Exergy is destructed due to irreversibilities within the system. The entropy generation defined by the second-law of thermodynamics is the measure of irreversibilities. The relation between the entropy generation $\dot{S}_{gen}$ and the lost of available work $\dot{W}_{lost}$ is given by the Gouy – Stodole theorem (Wylen et al. 1993; Bejan, 1979; Moran and Shapiro, 2004) written by

$$\dot{W}_{lost} = T_0 \dot{S}_{gen} \tag{1}$$

where T_0 is the environmental absolute temperature. The Gouy –Stodole theorem states that the lost available work i.e. exergy destruction is directly proportional to the entropy generation. Exergy is maximum theoretical work, i.e. corresponds to the definition of available work. Therefore, Eq. (1) can be rewritten as

$$\dot{E}_{xd} = T_0 \dot{S}_{gen} \tag{2}$$

to follow progressive literature on exergy.

In a convective system $\dot{E}_{xd}$ can be derived in an explicit form by following a hierarchical derivation which is necessary to supply a clear physical insight in order to make the reader follow easily the path from the fundamental equations of entropy generation to the exergy destruction.

LOSS OF WORK

The energy transport equations written for a convective transient system constitute the best starting point to derive the rate of exergy destruction explicitly. In vector-tensor notation the rate of accumulation of internal and kinetic energies per unit volume by considering the equation of continuity is (Bird et al. 1960)

$$\rho \frac{D}{Dt}\left(\hat{U} + \frac{1}{2}\mathrm{V}^2\right) = -\left(\tilde{\mathbf{N}}.\mathbf{q}\right) + \rho\left(\mathbf{V}.\mathbf{g}\right) - \left(\tilde{\mathbf{N}}.p\mathbf{V}\right) - \left(\tilde{\mathbf{N}}.\left[\boldsymbol{\tau}.\mathbf{V}\right]\right) \tag{3}$$

where $\hat{U}$ is the internal energy per unit mass of the fluid and $\mathbf{V}$ is the local velocity of fluid. The term on the left hand side is the rate of accumulation of energy and equals to the collective contribution of energy input by conduction, $\left(\tilde{\mathbf{N}}.\mathbf{q}\right)$, work done by gravitational force $\rho\left(\mathbf{V}.\mathbf{g}\right)$, pressure $\left(\tilde{\mathbf{N}}.p\mathbf{V}\right)$, and viscous $\left(\tilde{\mathbf{N}}.\left[\boldsymbol{\tau}.\mathbf{V}\right]\right)$ forces on the fluid per unit volume. When the equations of mechanical and thermal energies are considered separately, identification of mutually dependent terms become possible. The equation of mechanical energy is

$$\rho \frac{D}{Dt}\left(\frac{1}{2}\mathrm{V}^2\right) = -p\left(\tilde{\mathbf{N}}\,.\mathbf{V}\right) - \left(\tilde{\mathbf{N}}\,.p\mathbf{V}\right) + \rho\left(\mathbf{V.g}\right)$$
$$-\left(\tilde{\mathbf{N}}\,.[\boldsymbol{\tau}.\mathbf{V}]\right) - \left(\boldsymbol{\tau}:\tilde{\mathbf{N}}\,\mathbf{V}\right) \tag{4}$$

and the equation of thermal energy in terms of internal energy is

$$\rho \frac{D\hat{U}}{Dt} = -\left(\tilde{\mathbf{N}}\,.\mathbf{q}\right) - p\left(\tilde{\mathbf{N}}\,.\mathbf{V}\right) + \left(\boldsymbol{\tau}:\tilde{\mathbf{N}}\,\mathbf{V}\right) \tag{5}$$

The original forms of terms in Eq. (3) are observed in Eqs. (4) and (5). It is observed that two terms, $p\left(\tilde{\mathbf{N}}\,.\mathbf{V}\right)$ and $\left(\boldsymbol{\tau}:\tilde{\mathbf{N}}\,\mathbf{V}\right)$ are found mutually in Eqs. (4) and (5) with opposite signs. The term, $p\left(\tilde{\mathbf{N}}\,.\mathbf{V}\right)$, represents the rate of reversible conversion of mechanical energy to internal energy per unit volume due to work done by the fluid against the pressure at the faces of the control volume. Second term, $\left(\boldsymbol{\tau}:\tilde{\mathbf{N}}\,\mathbf{V}\right)$, is the rate of irreversible conversion of mechanical energy to internal energy per unit volume due to viscous forces. In Cartesian coordinates for incompressible Newtonian fluids the term has the following explicit form (Bird et al. 1960)

$$\left(-\boldsymbol{\tau}:\tilde{\mathbf{N}}\,\mathbf{V}\right) = \mu\Phi$$
$$= \frac{1}{2}\mu \sum_{\mathrm{i}} \sum_{\mathrm{j}} \left[\left(\frac{\partial v_{\mathrm{i}}}{\partial x_{\mathrm{j}}} + \frac{\partial v_{\mathrm{j}}}{\partial x_{\mathrm{i}}}\right) - \frac{2}{3}\left(\tilde{\mathbf{N}}\,.\mathbf{V}\right)\delta_{\mathrm{ij}}\right]^2 \, . \tag{6}$$

Here Φ is viscous dissipation function, i and j are x, y, and z, and δ_{ij} is the cronecker delta. It is provided by thermodynamics that $\mu\Phi$ accounts for heat added to the fluid flowing through the control volume due to internal irreversibilities indicating the loss of work that we seek.

EQUATION FOR ENTROPY GENERATION

In vector-tensor notation the entropy transport equation is written (Bejan, 1979; Moran and Shapiro, 2004; Bird et al. 1960) as

$$\rho \frac{D\hat{S}}{Dt} = -\left(\tilde{\mathbf{N}}\,.\mathbf{s}\right) + \dot{S}_{gen} \tag{7}$$

where $\hat{S}$ is the entropy per unit mass, $\mathbf{s}$ an entropy flux associated with heat transfer and measured with respect to the fluid velocity $\mathbf{V}$, and $\dot{S}_{gen}$ is the rate of entropy generation of all local irreversibilities per unit volume. The local entropy flux is equal to

$$\mathbf{s} = \frac{\mathbf{q}}{T} \tag{8}$$

where T is local temperature of the surface through which heat is transferred. By applying the rule for differentiation of products

$$\tilde{\mathbf{N}}\,.\mathbf{s} = \tilde{\mathbf{N}}\,.\frac{\mathbf{q}}{T} = \frac{1}{T}\left(\tilde{\mathbf{N}}\,.\mathbf{q}\right) - \frac{1}{T^2}\left(\mathbf{q}.\tilde{\mathbf{N}}\,\mathrm{T}\right) \tag{9}$$

is written. When Eq. (9) is inserted into Eq. (7), the rate of change of entropy becomes

$$\rho \frac{D\hat{S}}{Dt} = -\frac{1}{T}\left(\tilde{\mathbf{N}}\,.\mathbf{q}\right) + \frac{1}{T^2}\left(\mathbf{q}.\tilde{\mathbf{N}}\,\mathrm{T}\right) + \dot{S}_{gen}$$

or

$$\dot{S}_{gen} = \frac{1}{T}\left(\tilde{\mathbf{N}}\,.\mathbf{q}\right) - \frac{1}{T^2}\left(\mathbf{q}.\tilde{\mathbf{N}}\,\mathrm{T}\right) + \rho \frac{D\hat{S}}{Dt} \, . \tag{10}$$

On the other hand internal energy $\hat{U}$ is related to $\hat{S}$ and $\hat{V}$ the volume per unit mass, via the canonical thermodynamic relation given as

$$d\hat{U} = Td\hat{S} - pd\hat{V} \, . \tag{11}$$

The substantial derivative of Eq. (11) becomes

$$\frac{D\hat{U}}{Dt} = T\left(\frac{D\hat{S}}{Dt}\right) - p\left(\frac{D\hat{V}}{Dt}\right) \tag{12a}$$

Multiplying the both sides of Eq. (12a) by ρ,

$$\rho \frac{D\hat{U}}{Dt} = T\left(\rho \frac{D\hat{S}}{Dt}\right) - p\left(\rho \frac{D\hat{V}}{Dt}\right) \tag{12}$$

is obtained. Considering the continuity, following transformation

$$\rho \frac{D\hat{V}}{Dt} = \rho \frac{D}{Dt}\left(\frac{1}{\rho}\right) = -\frac{1}{\rho}\frac{D\rho}{Dt} = \left(\tilde{\mathbf{N}}\,.\mathbf{V}\right) \tag{13}$$

is written. When Eq. (13) is used in Eq. (12),

$$\rho \frac{D\hat{U}}{Dt} = T\left(\rho \frac{D\hat{S}}{Dt}\right) - p\left(\tilde{\mathbf{N}}\,.\mathbf{V}\right) \tag{14}$$

is obtained. Thermal energy equation given by Eq. (5) is used in Eq. (14) to get the rate of change of entropy as follows

$$\rho \frac{D\hat{S}}{Dt} = -\frac{1}{T}\left(\tilde{\mathbf{N}}\,.\mathbf{q}\right) + \frac{1}{T}\left(\boldsymbol{\tau} : \tilde{\mathbf{N}}\,\mathbf{V}\right) \tag{15}$$

Hence the rate of entropy generation is obtained by inserting Eq. (15) into Eq. (10). After some manipulation

$$\dot{S}_{gen} = -\frac{1}{T^2}\left(\mathbf{q}.\tilde{\mathbf{N}}\,\mathrm{T}\right) + \frac{1}{T}\left(\boldsymbol{\tau} : \tilde{\mathbf{N}}\,\mathbf{V}\right) \tag{16}$$

is obtained. This expression states that the rate of entropy generation is the sum of two terms; the entropy generation associated with irreversibility due to heat transfer thorough out the interior of the control volume of fluid over a finite temperature difference $\tilde{\mathbf{N}}\,\mathrm{T}$ and the positive internal- irreversibility entropy generation term due to viscous forces. In a non-isothermal flow system there is conductive heat transfer between molecules along with the fluid motion. Fourier's law of conduction for isotropic media explains the relation between the heat flux and temperature gradient as follows

$$\mathbf{q} = k\tilde{\mathbf{N}}\,\mathrm{T} \tag{17}$$

Here k is the proportionality constant named thermal conductivity and represents the characteristics of matter for heat transfer capability. When Eq. (17) and Eq. (6) are used in Eq. (16), the rate of entropy generation per unit volume becomes (Bejan, 1979; Bejan, 1980; Bejan, 1994)

$$\dot{S}_{gen} = \frac{k}{T^2}\left(\tilde{\mathbf{N}}\,\mathrm{T}\right)^2 + \frac{\mu}{T}\Phi \tag{18}$$

Providing the temperature and velocity distributions throughout the control volume in a convective flow system, $\dot{S}_{gen}$ can be calculated. The local temperature, T, should be evaluated attentively during the second law analyses of thermal systems.

EQUATION FOR FLOW EXERGY DESTRUCTION

The equation for flow exergy destruction presented by Eq. (2) is obtained by using Eq. (18) as

$$\dot{E}_{xd} = T_0\left[\frac{k}{T^2}\left(\tilde{\mathbf{N}}\,\mathrm{T}\right)^2 + \frac{\mu}{T}\Phi\right] \tag{19}$$

For evaluating $\dot{E}_{xd}$ quantitatively it is necessary to be written more explicitly by using the exact definition of the flow system. For two-dimensional Cartesian flow system $\dot{E}_{xd}$ becomes

$$\dot{E}_{xd} = T_0\left\{\frac{k}{T^2}\left[\left(\frac{\partial \mathrm{T}}{\partial x}\right)^2 + \left(\frac{\partial \mathrm{T}}{\partial y}\right)^2\right]\right\} + T_0\left\{2\frac{\mu}{T}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] + \frac{\mu}{T}\left[\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right]\right\} \tag{20}$$

Obviously the exergy destruction is calculated as a post-processed derived quantity after providing the velocity and temperature distributions. The environmental absolute temperature, T_0, and the local absolute temperature, T, should be handled attentively, which effects directly the results of analysis for exergy destruction. The local temperature T is taken typically as the temperature of the walls of control volume. For overall entropy generation in case of external flows, the local absolute temperature is treated as that of the body or undisturbed external fluid by assuming that difference between these temperatures is much smaller that either absolute temperature of the body or fluid. When the temperature variation over the body cross-section is negligible compared with the absolute temperature, T is taken as equal to T_0 characteristic absolute temperature (Bejan, 1979). During internal flows T is most probably considered as the inlet fluid temperature (Erbay et al, 2007a; Erbay et al, 2007b; Erbay et al, 2003a). For examples of enclosure problems (Erbay et al, 2003b; Erbay et al, 2004) it is observed that T is taken as an average of hot and cold wall temperatures. In the literature it is observed that T is taken depending on the nature of the problem (Mahmud and Fraser, 2002; Ko and Ting, 2005). These alternatives may suppose a researcher to be in dubious situation therefore the researcher must comprehend the fundamental characteristics of his/her own problem.

GOVERNING EQUATIONS

The governing equations consisting of continuity, momentum and energy equations are necessary to solved calculating the post processed quantity exergy destruction within a fluid flowing in a duct written preferably in dimensionless forms for numerical solutions. From here on using superscript "* " for representing dimensional forms of the terms to get easy outlook, the following set of dimensionless transient governing equations and entropy generation are considered for incompressible Newtonian fluids;

$$\left(\nabla.\mathbf{V}\right) = 0 \tag{21}$$

$$\rho \frac{D\mathbf{V}}{Dt} = -\nabla \mathrm{p} + \frac{1}{\mathrm{Re}} \nabla^2 \mathbf{V} \tag{22}$$

$$\frac{DT}{Dt} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}} \nabla^2 T \quad . \tag{23}$$

The set of governing equations can be given by considering two-dimensional Cartesian coordinates as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{24}$$

$$\frac{\partial(\rho u)}{\partial t} + u\frac{\partial(\rho u)}{\partial x} + v\frac{\partial(\rho u)}{\partial y} = -\frac{\partial P}{\partial x} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{25}$$

$$\frac{\partial(\rho v)}{\partial t} + u\frac{\partial(\rho v)}{\partial x} + v\frac{\partial(\rho v)}{\partial y} = -\frac{\partial P}{\partial y} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{26}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{27}$$

where

$$\mathrm{Re} = \frac{u_0 D}{\nu},\ \mathrm{Pr} = \frac{\nu}{\alpha},\ x = \frac{x^*}{D},\ y = \frac{y^*}{D},\ t = \frac{t^* u_0}{D}$$
$$u = \frac{u^*}{u_0},\quad v = \frac{v^*}{u_0},\quad \rho = \frac{\rho^*}{\rho_0}$$
$$P = \frac{p^*}{\rho_0 u_0^2},\qquad T = \frac{T^* - T_{in}}{T_{wall} - T_{in}} \tag{28}$$

The dimensionless entropy generation is obtained as

$$N_s = \left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right] + \phi\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right\} \tag{29}$$

by using the following parameters

$$N_s = \dot{S}'''_{gen}\frac{D^2}{k\ \Omega^2},\quad \phi = \frac{Br}{\Omega},\quad Br = \frac{u_0^2 \mu}{k\ \Delta T},$$
$$\Omega = \frac{\Delta T}{T_{in}},\quad \Delta T = T_{wall} - T_{in} \tag{30}$$

CALCULATION OF EXERGY DESTRUCTION

The rate of exergy destruction in connection with the dimensionless solutions can be calculated. The dimensionless entropy generation number N_s given in Eq. (29) is calculated for various Reynolds numbers, Brinkman numbers, and wall - fluid temperatures for various fluids. The entropy generation per unit volume $\dot{S}'''_{gen}$ is extracted from the dimensionless entropy generation number N_s as

$$\dot{S}'''_{gen} = N_s\frac{k\ \Omega^2}{D^2} = N_s\frac{k\left(\frac{\Delta T}{T_{in}}\right)^2}{D^2} = N_s\frac{k\left(\frac{T_{wall}-T_{in}}{T_{in}}\right)^2}{D^2} = N_s\frac{k}{D^2}\left(\frac{T_{wall}-T_{in}}{T_{in}}\right)^2 \tag{31}$$

By substituting Eq. (31) into Eq. (2), the rate of exergy destruction per unit volume becomes

$$\dot{E}_{xd} = T_0\dot{S}_{gen} = T_0\left\{N_s\frac{k}{D^2}\left(\frac{T_{wall}-T_{in}}{T_{in}}\right)^2\right\} \tag{32}$$

Or

$$\dot{E}_{xd} = N_s\dot{E}_{xdf} \tag{33}$$

where $\dot{E}_{xdf}$ can be called as *exergy destruction factor*. Considering Eq. (33), *exergy destruction factor* is a group of parameters given by

$$\dot{E}_{xdf} = T_0\frac{k}{D^2}\left(\frac{T_{wall}-T_{in}}{T_{in}}\right)^2. \tag{34}$$

In an analysis of energy-exergy losses there is no need to get absolute values at the beginning. The fact is to learn the places at which losses are greater that others and hence relative values are good indicators. Therefore, normalized exergy destruction values are sufficient to describe the volumetric exergy destruction rates in a given geometry for a certain fluid under prescribed thermal hydraulic conditions. Normalized exergy is calculated by

$$\overline{E}_{xd} = \frac{\dot{E}_{xd}}{\dot{E}_{xd\,\max}} \tag{35}$$

The solution procedure for numerical applications are simple. The dimensionless entropy generation number, N_s, is solved first. If exergy is required, Eq. (35) is used without hesitation. For the dimensional studies when dimensional and absolute results are necessary, then *exergy destruction factor* becomes necessary and is supplied by Eq. (34).

CONCLUSION

The engineering functions of ducts are to transfer heat and fluid in the mechanical installation. The quantities that affect the energy utilization performance of the convective duct flow are the heat transfer rate and irreversibility. The irreversibility is an indicator of the destruction of available work measured by exergy destruction; therefore, second law analysis is necessarily applied on convective systems to investigate the exergy destruction rate.

In this study, the derivation of the rate of exergy destruction equation and the calculation of exergy destruction rate indicating the whole set of governing equations have been given. It is said that $\dot{E}_{xd}$ can be found quantitatively from Eq. (32) providing the temperature and velocity distributions by numerical solution of the sets of governing equations from Eq. (21) to (23), for the entropy generation number N_s by Eq. (29) and supplying the parameters for *exergy destruction factor* on the right hand side of Eq. (34). Obviously the normalized exergy destruction number, $\overline{E}_{xd}$, can be obtained with Eq. (35) by giving attention to the environmental absolute temperature, T_0, and the local absolute temperature, T. Foregoing analysis of $\dot{E}_{xd}$ is continuing and will be presented in the next study.

Analysis of the exergy destruction is important in upgrading the system performances. The numerical techniques are very helpful for analyzing the effect of all parameters separately. Therefore the comments on the numerical results obtained from the idealized physical model have powerful importance on practical applications to abstain from misleading findings.

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