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The entropy generation for a rotating sphere under uniform heat flux boundary condition in forced-convection flow

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Abstract

Purpose – The purpose of this paper is to investigate the problem of entropy generation around a spinning/non-spinning solid sphere subjected to uniform heat flux boundary condition in the forced-convection regime.

Design/methodology/approach – The governing continuity, momentum, energy and entropy generation equations are numerically solved for a wide range of the controlling parameters; Reynolds number and the dimensionless spin number.

Findings – The dimensionless overall total entropy generation increases with the dimensionless spin number. The effect of increasing the spin number on the fluid-friction component of entropy generation is more significant compared to its effect on heat transfer entropy generation.

Research limitations/implications – Since the boundary-layer analysis is used, the flow is presented up to only the point of external flow separation.

Practical implications – Entropy generation analysis can be used to evaluate the design of many heat transfer systems and suggest design improvements.

Originality/value – A review in the open literature indicated that no study is available for the entropy generation in the unconfined flow case about a spinning sphere.

Keywords Thermodynamic properties, Boundary layers, Flow, Rotational motion, Heat transfer

Paper type Research paper

Nomenclature

a	sphere radius
Be	Bejan number, S_{HT}/S_{total}
c_P	specific heat at constant pressure
h	local heat transfer coefficient
k	thermal conductivity of fluid
K*	interior-to-exterior thermal conductivity ratio
m	number of steps of the numerical mesh network in the x-direction
n	number of steps of the numerical mesh network in the z-direction
Nu	Nusselt number, $2ah/k$
Pr	prandtl number, ν/α
q	heat flux
r	radial coordinate measured from the sphere's center
Re	Reynolds number, $2U_\infty a/\nu$
s_g	total (due to both heat transfer and fluid friction) entropy generation per unit volume
S_g	dimensionless total entropy generation per unit volume given by Equation (6), $s_g a^2/k$

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SHT	dimensionless entropy generation due to only heat transfer
SF	dimensionless entropy generation due to only fluid friction
S_{Total}	total entropy generation due to both fluid friction and heat transfer, $= S_{g,overall} = \iint S_g$ dZ dX
t	temperature
t_w	wall temperature
t_∞	free stream temperature
T	dimensionless temperature, $T = k(t - t_\infty)/(aq)$
Ta	Taylor number, $\mathrm{Ta} = 4\Omega^2 a^4/\nu^2$
T_w	dimensionless wall temperature, $T_w = k(t_w - t_\infty)/(aq)$
u	meridional (x-direction) component of velocity
U	dimensionless meridional component of velocity, u/U_∞
u*	velocity component in x-direction for the potential flow outside the external boundary layer, $-(\partial\psi/\partial \mathrm{r})/(\mathrm{r}\sin\theta) = \mathrm{U}_\infty \sin\theta[1 + \mathrm{a}^3/(2\mathrm{r}^3)]$
U*	dimensionless potential velocity component in the x-direction for external flow, $\mathrm{u}^*/\mathrm{U}_\infty$
U_∞	free stream velocity in the exterior flow
V	azimuthal velocity component at any point
v_o	circumferential velocity at the sphere's surface, $v_o = \Omega \mathrm{r_o}$
V	dimensionless azimuthal velocity component, $\mathrm{V} = \mathrm{v}/\Omega \mathrm{a}$
V_o	dimensionless azimuthal velocity component at the sphere's surface, $\mathrm{V_o} = \mathrm{r_o}/\mathrm{a}$
w	radial (z-direction) velocity component
w*	radial (z-direction) velocity component for potential flow outside the external boundary layer, $(\partial\psi/\partial\theta)/(\mathrm{r}^2\sin\theta) = -\mathrm{U}_\infty \cos\theta[1 - \mathrm{a}^3/\mathrm{r}^3]$
W	dimensionless radial velocity component, w/U_∞
W*	dimensionless radial velocity component for the external potential flow, $\mathrm{w}^*/\mathrm{U}_\infty$
X	meridional distance (along the circular generator of the sphere's surface) measured from the stagnation point
$\bar{\mathrm{x}}$	the projection of the meridional coordinate x on the axis of symmetry (sphere diameter coincident with the stagnation line)
X	dimensionless meridional distance along the surface measured from the stagnation point, 2x/Re a
Z	distance from the sphere's surface measured along the normal to the surface in the radial direction, being positive for the external flow and negative inside the sphere
Z	dimensionless distance perpendicular to the surface in the radial direction, z/a

Greek symbols

δ	boundary layer thickness
θ	center angle measured from the frontal stagnation line.
μ	dynamic fluid viscosity
μ*	interior-to-exterior (liquid-to-gas) dynamic viscosity ratio
α	thermal diffusivity, $K/\rho C_p$
τ'	meridional shear stress at the sphere surface, $\mu \frac{\partial \mathrm{U}}{\partial \mathrm{Z}}\Big\vert_{\mathrm{o}}$

τ	dimensionless shear stress, $\tau' \sqrt{\mathrm{Re}/2}/(\rho U_{\infty}^2)$
ϕ	third spherical polar coordinate
ψ	stream function of external potential flow far away from the sphere, given by $\psi = 0.5 u_{\infty} r^2 \sin^2 \theta(1-(a^3/r^3))$
Ω	sphere angular velocity

Subscripts

F	fluid friction component
g	gas phase
H.T	heat transfer component
o	on the sphere surface
s	at separation point
x	in the meridional direction

Introduction

The problem of convection heat transfer around a sphere has gained enormous attention in the literature due to its practicality in a wide range of industrial and scientific applications. Moreover, entropy generation analysis can be used to evaluate the design of many heat transfer systems and suggest design improvements. Two main factors are responsible for entropy generation, namely, heat transfer across a finite temperature difference and viscous friction. Enhancement concepts that improve heat transfer should be considered for a better design of such equipment and therefore reduce thermodynamic losses. Drost and White (1994) analysed the performance of a heat pipe based on second law analysis and considered this analysis to be better than the efficiency index for performance evaluation. Khalkhali *et al.* (1999) reported that the convection heat transfer coefficient can be adjusted to minimize entropy generation in a heat pipe system. They performed a parametric study in which the effects of various heat pump parameters on entropy generations are examined. Demirel *et al.* (1996) calculated the entropy generation to analyze convective heat transfer in a rectangular packed bed. Entropy generation per unit volume were expressed analytically and graphically. The entropy generation maps they obtained reveal regions of excessive entropy generation

The energy and exergy analysis in the process of spray evaporation was performed (Som and Dash, 1993). They considered the law of entropy generation presented in their earlier work as fundamental equation to evaluate entropy generation rate due to evaporation. They have also developed a theoretical model for exergy analysis of the process. The minimization of entropy, its relation with fluid flow and heat transfer problems was explained in detail (Fowler and Bejan, 1994) and in great detail Bejan (1996) who expressed the equations of entropy generation for various cases and in different flow geometries. One of the main objectives of this investigation is the computation of entropy generation around solid spheres in an air stream ($\mathrm{Pr} = 0.7$). A thorough search of the literature has revealed that this problem has not been tackled yet. Therefore, the following summarizes the work done on flow around rotating solid/liquid spheres in a gas stream.

Schlichting (1953), who used a momentum integral technique, and Hoskins (1954) reported that the separation point of laminar boundary layer at the rear hemisphere is advanced due to solid sphere rotation. The three dimensional flow around a spinning body of revolution was analyzed by Parr (1964) using the boundary-layer theory. El-Shaarawi *et al.* (1987a) have studied experimentally the laminar flow around a rotating sphere in an air stream at a Reynolds number $\mathrm{Re} = 10{,}000$ and for spinning parameter ($\mathrm{Ta}/\mathrm{Re}^2$) values of 0, 1 and 5. El-Shaarawi *et al.* (1985, 1987b) developed a finite-difference scheme for solving the boundary-layer equations governing the laminar flow about a rotating solid sphere in an air stream parallel to the direction of the axis of rotation for high values of Reynolds number and spin parameter. They also reported that increasing the spin parameter (Ta/Re^2) shifts the point of laminar flow separation forward. The induced laminar flow due to rotating solid sphere in a quiescent environment was also studied numerically by El-Shaarawi *et al.* (1993). Rao and Sekhar (1993) analyzed numerically the axisymmetric rotating flow around a spinning solid sphere at small Reynolds numbers such that the diameter about which the sphere spins lies along the axis of the rotating fluid. They solved the complete Navier-Stokes equations in the stream function-vorticity format. Schmitt (1997) analyzed the viscous flow around a sphere spinning at a constant angular velocity for large Reynolds numbers.

The unsteady boundary-layer flow past an impulsively started translating and spinning rotational symmetric body was studied by Ece (1992) where the stream function and velocity swirl component were expanded in series powers of time. He reported that the sphere rotation reduces the drag and the separation angle. Ferriera *et al.* (1998) studied analytically the transient motion of a dense rigid sphere falling in light liquid. They obtained closed form solutions of instantaneous position, velocity and acceleration of the sphere under the influence of gravity through an incompressible Newtonian fluid subject to an Oseen-type drag relationship.

Karlo and Tezduvar (1998) used a finite-element method to investigate the three-dimensional unsteady flow past a sphere. Raghavarao and Pramadavalli (1989a, b) studied the flow of steady incompressible fluid rotating with a constant angular velocity and moving past a sphere for small values of Reynolds numbers where the Navier-Stokes equations were linearized using the Oseen approximation. They concluded that the rotation decreased the values of the stream function. Then, they solved the nonlinear Navier-Stokes equations numerically in the stream function-vorticity form and compared the results of their two models. The unsteady flow past a sphere was investigated numerically for oscillatory and accelerated motion respectively by Chang and Maxey (1994, 1995) at low to moderate Reynolds numbers. Hase and Weigand (2003) studied numerically heat transfer enhancement due to droplet deformation at high Reynolds numbers (up to $Re = 853$). Time dependednt heat and fluid flow around and inside a a single rising bubble was investigated numerically by Lai *et al.* (2006) using axisymmetric bounary-fitted mesh.

El-Shaarawi *et al.* (1997) considered the flow about and inside a liquid sphere moving steadily in another immiscible fluid; boundary-layer equations were used to investigate the flow field for large values of Reynolds number and for a wide range of interior-to-exterior viscosity ratio. The shear stress on the fluid-sphere-surface induces internal motion inside the sphere which can be represented by the well known Hill's vortex. However, the strength of the vortex is reduced because of the presence of the boundary layer in the liquid phase. Antar and El-Shaarawi (2002) studied the effect of viscosity, spin and Reynolds number on the flow characteristics about a liquid sphere in a gas stream. Antar and El-Shaarawi (2008) investigated the entropy generation around a solid non-rotating sphere in forced-convection flow and uniform heat flux boundary condition. They reported that the heat tranfer component of the entropy generation is an order of magnitude higher than the fluid friction component for $Pr = 0.7$. However, as the value of Pr increases, entropy generation due to fluid friction becomes significant and it dominates for Prandtl number values > 7.

It appears from the literature survey that entropy generation in confined flows were reported in Bejan (1996), Sahin (1996, 1998), Datta (2000) and Yilbas *et al.* (1999) However, to the best of the authors knowledge, other than the work carried out by

Abu-hijleh *et al.* (1998, 1999) and Haddad *et al.* (2000) for entropy generation due to laminar natural/forced convection over a cylinder and Antar and El-Shaarawi (2008) for entropy generation around a solid non-rotating sphere in forced-convection flow, no study is available for studying the entropy generation in the unconfined flow case about a sphere.

This study is aimed at investigating the effect of forced-convection and rotation on the entropy generation around a solid sphere subjected to uniform heat flux boundary conditions. This work is believed to contribute in covering a gap in the open literature on entropy generation in external flows around non-rotating/rotating objects in forced-convection flow field.

Problem formulation

Flow field

Figure 1 shows the problem under consideration and the coordinate system. The flow field is assumed to be axisymmetric ($\partial/\partial\varphi = 0$) and the fluid has constant properties. The effects of chemical reaction, compressibility and surface active impurities are considered to be absent. Reynolds number is assumed large enough for the boundary-layer model to be applied.

Using the dimensionless parameters given in the nomenclature, the non-dimensional continuity, momentum and energy equations are given by El-Shaarawi *et al.* (1985, 1990) as:

Mass conservation

$$\frac{\partial U}{\partial X} + \frac{\mathrm{Re}}{2}\frac{\partial W}{\partial Z} + \frac{U}{R}\frac{dR}{dX} + \mathrm{Re}\frac{W}{1+Z} = 0 \tag{1}$$

Momentum conservation in meridional direction

$$U\frac{\partial U}{\partial X} + \frac{\mathrm{Re}\,W}{2}\frac{\partial U}{\partial Z} - \frac{Ta}{\mathrm{Re}^2}\frac{V^2}{R_o}\frac{dR_o}{dX_o} = U^*\frac{\partial U^*}{\partial X} + \frac{\partial^2 U}{\partial Z^2} \tag{2}$$

Momentum conservation in the azimuthal direction

$$U\frac{\partial V}{\partial X} + \frac{\mathrm{Re}\,W}{2}\frac{\partial V}{\partial Z} + \frac{UV}{R_o}\frac{dR_o}{dX_o} = \frac{\partial^2 V}{\partial Z^2} \tag{3}$$

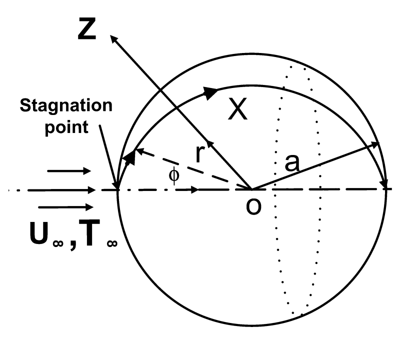

Figure 1.
Coordinate system

Energy equation

$$U\frac{\partial T}{\partial X}+\frac{\mathrm{Re}\,W}{2}\frac{\partial T}{\partial Z}=\frac{1}{\mathrm{Pr}}\frac{\partial^2 T}{\partial Z^2} \tag{4}$$

The above equations are coupled and subject to the following boundary conditions.

$$\left.\begin{array}{l}\mathrm{For\ Z=0, X=0\ (stagnation\ point): U=W=V=0,\quad T=T_\infty}\\ \mathrm{For\ Z=\infty, X\geq 0\ (far\ away\ from\ the\ sphere): U=U^*, V=0, T=T_\infty}\\ \mathrm{For\ Z>0\ and\ X=0\ (front\ stagnation\ line): W=W^*, U=V=0, T=T_\infty}\\ \mathrm{For\ Z=0, X>0\ (sphere\ surface): U=0, V=}\dfrac{\mathrm{Re}}{2}R_o\end{array}\right\} \tag{5}$$

$\mathrm{W}=0, \mathrm{q}=$ constant for constant heat flux case

Calculation of the entropy generation

The local (at some point or location in the solution domain) total entropy generation is a result of heat transfer (through the temperature gradients) and fluid friction (through the velocity gradients). Viscous dissipation appears in both the energy equation and the entropy generation equation. Viscous dissipation should be considered in cases where velocities are near and higher than the sonic speeds and external fluid viscosity is sufficiently high. Usually, one can neglect the dissipation term in the energy equation (if the flow velocity is relatively low) whereas the dissipation term in the entropy generation equation could not be neglected. In the present paper, the dissipation term in the energy equation is neglected and the entropy generation per unit volume as given by Bejan (1996) is used. Accordingly, the local total entropy generation at a point in the flow field (which has two components, one due to heat transfer and the other due to fluid friction) is as follows:

$$\begin{aligned}S_g=&\frac{1}{T^2}\left[\left(\frac{\partial T}{\partial Z}\right)^2+\frac{4}{\mathrm{Re}^2}\left(\frac{\partial T}{\partial X}\right)^2\right]+\frac{\mathrm{Pr}Ec_m}{\dfrac{kt_\infty}{aq}+T}\\ &\times\left\{\begin{array}{l}2\left[\begin{array}{l}\left(\dfrac{\partial W}{\partial Z}\right)^2+\dfrac{4}{\mathrm{Re}^2}\left(\dfrac{\partial U}{\partial X}\right)^2+\dfrac{W^2}{(1+Z)^2}+\dfrac{4}{\mathrm{Re}}\left(\dfrac{\partial U}{\partial X}\right)\dfrac{W}{(1+Z)}\\ +\dfrac{W^2}{(1+Z)^2}+\dfrac{U^2Cot^2\theta}{(1+Z)^2}+\dfrac{2WUCot\theta}{(1+Z)^2}\end{array}\right]\\ +\left(\left(\dfrac{\partial U}{\partial Z}\right)^2+\dfrac{U^2}{(1+Z)^2}-2U\dfrac{\partial U}{\partial Z}\dfrac{1}{1+Z}\right)+\dfrac{4}{\mathrm{Re}^2}\left(\dfrac{\partial W}{\partial X}\right)^2\\ +\dfrac{4}{\mathrm{Re}}\left(\dfrac{\partial U}{\partial Z}\dfrac{1}{1+Z}-\dfrac{U}{(1+Z)^2}\right)\left(\dfrac{\partial W}{\partial X}\right)\end{array}\right\}\end{aligned} \tag{6}$$

where Ec_m here is the modified Eckert number given by: $Ec_m=U_\infty^2/(c_p(aq/k))$.

The quantity kt_∞/aq that appears in the above equation is a dimensionless value and it is a controlling parameter that depends on the values of the free stream temperature, the heat flux, the fluid thermal conductivity and radius of the sphere. Bejan number defined as the ratio between the heat-transfer component of the entropy generation to the total entropy generation, is calculated and presented as a function of the controlling parameters.

Numerical method of solution

The numerical grid is shown in Figure 2. A typical mesh point is (i, j) where i designates the progress in the radial direction and j pertains to the meridional direction. The value I = 1 represents the surface of the sphere and i increases in the radial direction till the edge of the boundary layer while j = 1 represents the front stagnation line and increases till the point of external flow separation is encountered and the numerical solution is stopped.

The details of the numerical method of solution are given by Antar and El-Shaarawi (2008) and only a pertinent brief is given here. The numerical solution starts by specifying the values of Re, Ec, Pr, Ta/Re^2, and kt_∞/aq. The azimuthal (V) momentum equation is solved for the second meridional step ($j = 2$, $i = 1, 2, \ldots, n - 1$) by applying Thomas method for solving the obtained ($n - 1$) simultaneous equations. Having calculated the values of V at the second meridional step, values of T at the second meridional step are similarly obtained using the energy equation. These values are used to solve the meridional (U) momentum equation using the same method for solving the obtained (n) equations in the meridional velocity values (U). Using the computed values of T and U in the second meridional step, values of W are obtained by solving the continuity equation through a step-by-step manner. After calculating the temperature within the boundary layer, the local entropy generation term is then calculated.

Then the solution is advanced for the next meridional step and the whole procedure is repeated till the point of external flow separation, which is characterized by the condition $\partial U/\partial Z = 0$, is reached. Selection of n is done as follows. An initial value of n will be assumed and then upon solving for the temperature, the value at the outermost point is compared with free stream temperature. If they are close within acceptable numerical tolerance, the solution is advanced to the next meridional station, otherwise the value of n will be increased and the solution is repeated for the same meridional

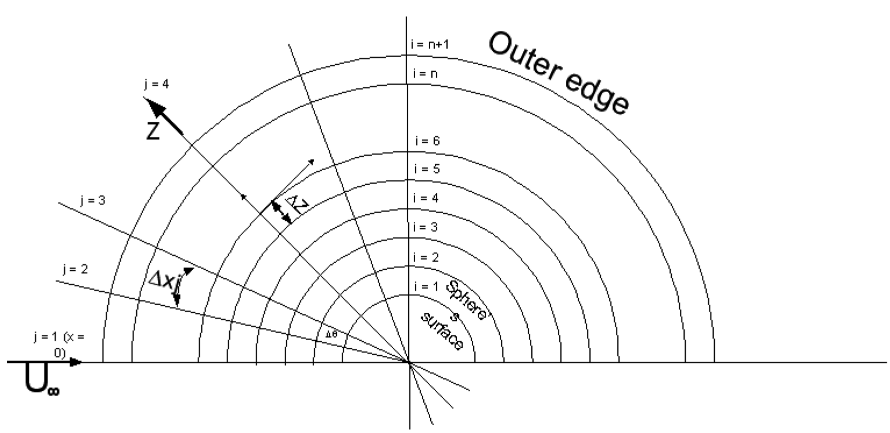

Figure 2.
Numerical grid

station until the computed values of T are accepted (if the same criterion is satisfied). In order to find the separation angle precisely, the following is adopted. When the point of separation is reached, the solution is stepped back to the previous meridional station and the increment $\Delta\theta$ is changed to a smaller value (usually one tenth of the used $\Delta\theta$) and the solution is continued to find the separation point accurately.

It is worth mentioning that grid independence was checked after the program was completed so that the obtained solution would be a grid independent one. In this respect, very fine grid was used in places where very high gradients exist (for example, near both the stagnation point and the point of external flow separation).

The overall total (due to both fluid friction and heat transfer) entropy generation can be obtained by integrating the local total (due to both fluid friction and heat transfer) entropy generation over the entire solution domain and is given by:

$$S_{Total} = S_{g,\,overall} = \int\int S_g \mathrm{dZ}\,\mathrm{dX}$$

Discussion of results

Validation of the present code

For the sake of validation of the present code, a comparison between this study and the previous work of Schlichting (1953) is shown Figure 3. This figure compares the present results of the wall shear stress in the meridional direction for a given Reynolds number with those of Schlichting (1953). It can be clearly seen that the results obtained by the code used in present study are in good agreement with previous published results. All the results presented in this paper are for $kt_\infty/aq = 0.1$

Effect of spinning on the entropy generation

The effect of spinning the solid sphere on the entropy generated in the boundary layer is presented and discussed in this section. Figure 4 shows the effect of spinning the sphere on the variation of the integrated (in the radial, i.e. Z, direction for each value of θ) local total entropy generation (due to both fluid friction and heat transfer) with θ (around the sphere) for given values of Reynolds number (Re) $=$ 10,000 and Ec $=$ 0.01.

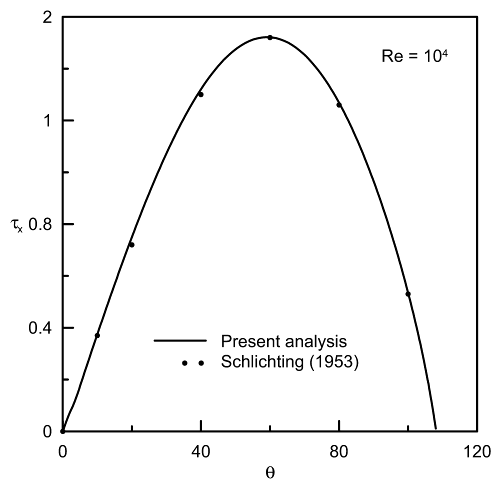

Figure 3.
Shear stress around the sphere

Spinning has a negligible effect for small spinning numbers (Ta/Re^2 = up to 100). However, as the spinning number is increased, an increase in the meridional velocity component occurs, leading to an increase in velocity gradients, temperature gradients and temperature. This increase in the meridional velocity is significant near the surface of the sphere, resulting in a fluid acceleration due to the centrifugal force that is caused by the rotation of the sphere. That all result in a significant increase in the entropy generated within the boundary layer. Increasing the spin number (Ta/Re^2) increases the entropy generated as shown in the figure.

For a given spinning number ($Ta/Re^2 = 5{,}000$) and a given $Ec = 0.01$, the variation with θ of the integrated local total entropy generation (i.e. entropy generated due to both heat transfer and fluid friction integrated in the radial, i.e. Z, direction for each value of θ) is shown in Figure 5 at different values of Reynolds number. Noting that for a given spinning number (Ta/Re^2) increasing Re implies an increase in the spinning velocity (i.e. an increase in the value of Ta), Figure 5 indicates that the simultaneous effect of increasing Reynolds number and spinning leads to a significant increase in the local average total entropy generation.

Figure 6 depicts the effect of Eckert number for given values of Reynolds number and the spin number (Ta/Re^2) on the variation of the integrated (in the radial direction) local total entropy generation with the meridional angle. Increasing the Eckert number increases the fluid-friction component of the entropy generation and accordingly higher integrated local total entropy generation values are reported. The point of maximum entropy generated is shifted forward in the meridional direction to match the location of maximum velocity around the sphere (in the vicinity of $\theta = 60$) at higher values of Eckert number ($Ec \geq 0.5$) which confirms the dominating effect of fluid-friction component of the entropy generation.

Figure 7 shows the variation of the overall (from front stagnation point till point of flow separation) entropy components, namely, heat transfer and fluid friction components with the spin number (Ta/Re^2) for given $Ec = 0.01$ and $Re = 10{,}000$.

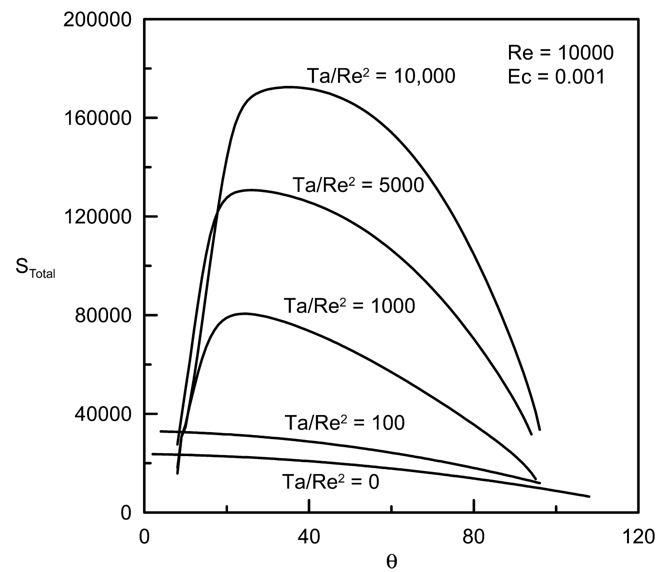

Figure 4.
Effect of rotation number on the local average entropy generation for $Re = 10^4$

Increasing the spin number increases the velocity gradient within the boundary layer and accordingly the temperature gradient (as the spinning number is increased, an increase in the meridional velocity component occurs near the surface of the sphere, resulting in a fluid acceleration due to the centrifugal force that is caused by the rotation of the sphere, leading to an increase in velocity gradients, (El-Shaarawi *et al.*, 1985; 1987b). However, the figure shows that the effect of increasing the spin number on the velocity gradient and hence the fluid-friction component of entropy generation is more compared with its effect on the heat-transfer component. As the spin parameter is increased significantly (approaching 10^4) the two components become of the same

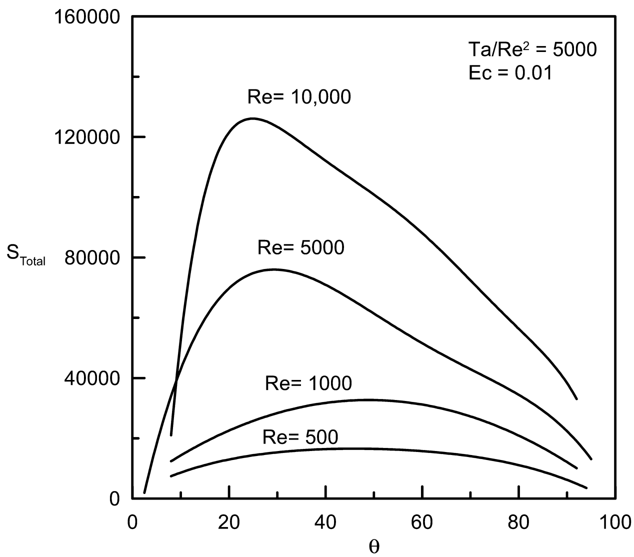

Figure 5.
Variation of the local average entropy generation with Re for $Ta/Re^2 = 5{,}000$ and $Ec = 0.01$

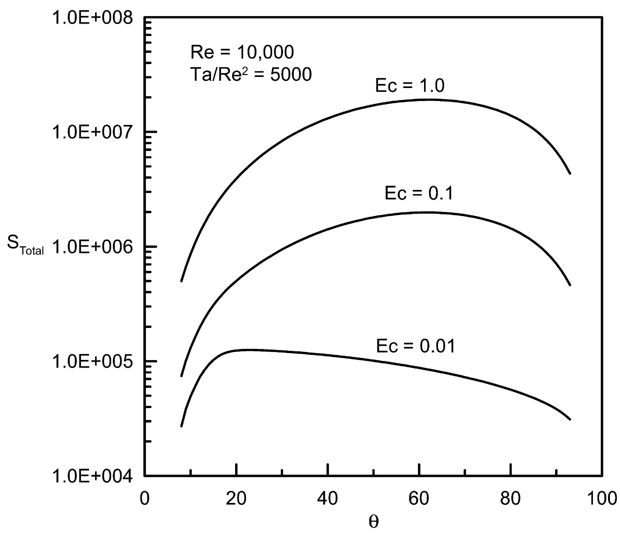

Figure 6.
Variation of the local average entropy generation with Ec for $Re = 10^4$ and $Ta/Re^2 = 5{,}000$

order of magnitude. This indicates values of the spin number at which we can actually have significant component of fluid-friction entropy generation. This figure also shows the changes of Bejan number (Be) with the spin number. Increasing the spin number increases both the fluid friction and heat transfer components of the entropy generated. However, since its effect on the fluid friction component is more compared with its effect on the heat transfer component, the Bejan number accordingly decreases.

The variation of the overall entropy generation with Reynolds number is shown in Figure 8 for Ec = 0.01 at a value of the spin number $Ta/Re^2 = 5{,}000$. One would anticipate that increasing Reynolds number would result in an increase in both fluid

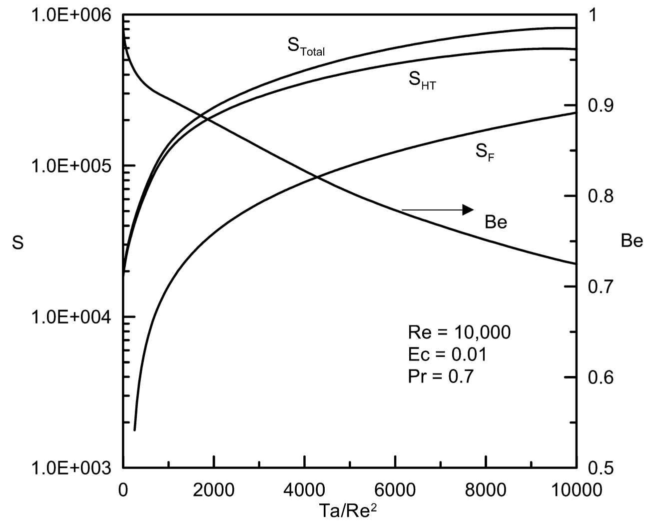

Figure 7.
Variation of total average entropy components with Ta/Re^2 for $Re = 10^4$ and Ec = 0.01

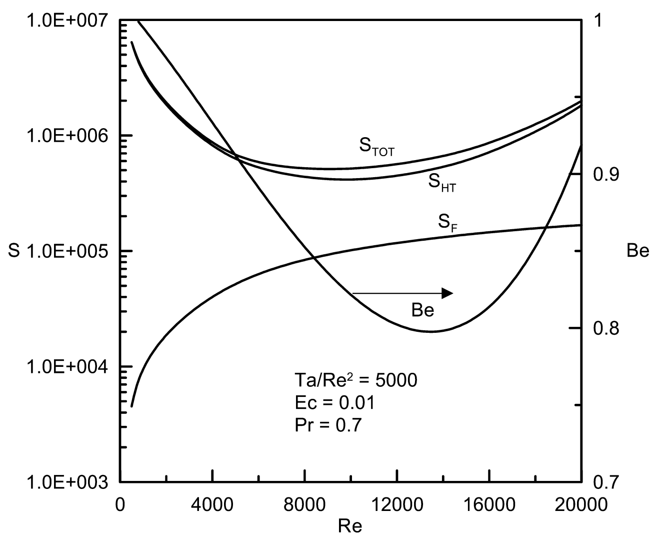

Figure 8.
Variation of the total average entropy components with Re for $Ta/Re^2 = 5{,}000$ and Ec = 0.01

friction and heat trasnfer components of the entropy generation. However, Figure 8 shows that at small values of Re, the heat-transfer component decreases and the fluid-friction component increases with Re. Nevertheless, the overall total entropy generation follows the trend of the heat transfer component. As the value of Re increases (Re > 2,000), the figure shows a decrease in the heat transfer component of the overall total entropy generation with Re up to a certain value of Re then it increases indicating a point of minumum heat transfer entropy generation. This has a significant effect on the overall total entropy generation at this low value of Ec as shown in the figure. This explains also the significant variation in the values of Bejan number (Be) as Re increases.

Significant values of fluid-friction component of the overall total entropy generation are expecetd at higher Eckert number values. This is shown in Figure 9 for given values of spin number (Ta/Re^2) of 5,000 and Re = 10,000. As the value of the Eckert number increases, the fluid friction component of the entropy generation becomes more significant till it dominates and becomes more than the heat transfer component. This trend is also indicated by the values of Bejan number that decrease with Ec indicating the significance of the fluid friction entropy generation. It may be noted here that the value at which the fluid friction component becomes equal in magnitude to the heat trasnfer component in this case is about 0.05 whereas results of non-spinning sphere indicate that, if spinning was absent, higher value of Ec number would be required to get the same effect of equal magnitudes of entropy generation components (heat trasnfer and fluid friction components).

Conclusions

The problem of entropy generation due to forced-convection flow around a rotating solid sphere in an air stream is solved numerically for uniform heat flux boundary conditions. The effects of Reynolds, the spin and Eckert numbers on the entropy generation were investigated. It has been observed that, for given Ec and Re, as the spin number (Ta/Re^2) is increased, the dimensionless overall total entropy generation increases constantly. However, the effect of increasing the spin number on the

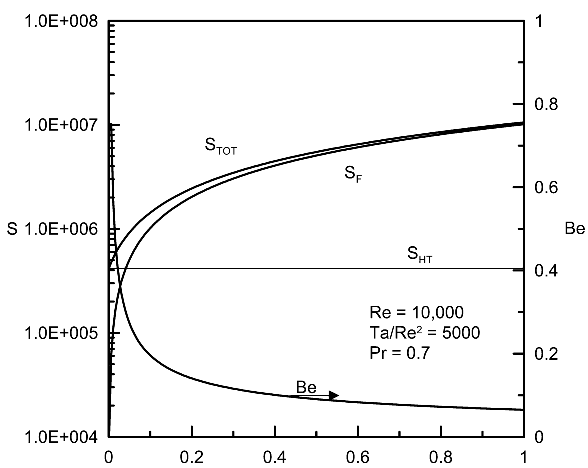

Figure 9.
Variation of the total average entropy components with Ec for Re = 10^4 and Ta/Re2 = 5,000

fluid-friction component of entropy generation is more compared with its effect on the heat transfer component. Consequently, as the spin parameter increases the Bejan number (Be) decreases; it reaches a value ≈ 0.73 at $Ta/Re^2 = 10^4$. A further increase in the spin number would make the fluid friction component of the entropy generated much more than the heat transfer component and accordingly the Bejan number is anticipated to further decrease to much less values.

At small values of Re, for given Ec and the spin number (Ta/Re^2), the heat transfer component of the entropy generated decreases while the fluid friction component increases with Re. Thus, the fluid friction component has a more significant effect at the small Re range on the total entropy generated. As the value of Re increases ($Re > 2,000$), the results show a decrease in the heat transfer component of the overall average entropy generation with Re up to a certain value of Re then it increases indicating a point of minumum heat transfer entropy generation.

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