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Thermodynamic analysis of a solid nuclear fuel element surrounded by flow of coolant through a concentric annular channel

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ABSTRACT

A continuous quest for efficient utilization of energy resources has motivated the researchers to search for optimal design and operating conditions during various energy conversion techniques. These conditions for such systems are often proposed by minimizing the destroyed exergy potential in course of the process. In the present paper a second law analysis is done for a nuclear fuel element inside a concentric annular coolant passage. The entropy generation analysis has been carried out through a conjugate approach, with steady state temperature profiles within the fuel element and a thermodynamic approach within fluid. The effect of solid core heat generation and the temperature gradients inside solid core, fuel-clad gap and cladding are considered as well along with the irreversibilities arising out of fluid flow under turbulent condition. The effect of Reynolds number, duty parameter, diameter ratio, Biot number, dimensionless heat flux and thermal conductivity ratios on overall entropy generation characteristics have been investigated and interpreted physically. The validation of the present calculations was confirmed by best-estimate thermal-hydraulic code RELAP. The new thermodynamic design methodology presented in this paper adheres to the safety limits in temperature. The present analysis can be extended for complex fuel pellet arrangements in subchannel structures by an “equivalent annulus model”.

1. Introduction

Determination of temperature distribution and heat transfer rate of reactor fuel pins play an important role in nuclear reactor design. The thermal energy removal from the fuel surface takes place due to different mechanisms of heat transfer. These include the fission of neutrons acting as a heat source; conduction through the solid fuel pin, clad and gap filler gas and convective heat transfer from clad surface to coolant. Thus each of the components of the system considered presents itself as a resistance to heat transfer from fuel pin centerline to bulk fluid flow. The mechanism of heat transfer from fuel to coolant has been analyzed by Tong (1967) and Todreas and Kazimi (1993a) using electrical circuit analogy.

In the present work a new thermal optimization technique and design methodology are proposed for fuel element design based on second law of thermodynamics. The contribution of various components of a fuel element and the factors having their consequences on the irreversibility associated with the energy removal from fuel elements can be best visualized by an “entropy generation analysis” (Bejan, 1982, 1995). In addition, this type of analysis of fuel element may also be useful in determining the optimal flow conditions that minimizes the overall irreversibility and the parameters having effect on these conditions.

In the present era of energy crisis we must think of utilizing the available energy at hand in an efficient manner by minimizing the losses due to various irreversibility sources. To achieve an enhanced energy removal from the fuel element surface, a forced flow of coolant is generally employed. This forced coolant through the surrounding annulus experiences irreversibilities arising out of surface to fluid temperature difference as well as the pressure drop

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Nomenclature

A_C	cross-sectional area of annulus, m^2
Bi	Biot number$(\overline{h}2r_c/k_c)$
C_p	specific heat, J/kg K
D	hydraulic diameter of the annulus $(2(r_o - r_c))$, m
D_e	equivalent diameter of the annulus $(2(r_o^2 - r_c^2)/r_c)$, m
f	Darcy friction factor
$\overline{h}$	heat transfer coefficient, W/m^2 K
h_g	gap conductance, W/m^2 K
k	thermal conductivity, W/m K
k_{r1}	fuel to cladding thermal conductivity ratio (k_s/k_c)
k_{r2}	fuel to gap thermal conductivity ratio (k_s/k_g)
k_{r3}	k_g/r_ih_g
L	length of the channel, m
$\dot{m}$	coolant mass flow rate, kg/s
Nu	Nusselt number (hD_e/k_f)
N_S	dimensionless overall entropy generation
p	pressure, Pa
P_w	wetted perimeter of the annulus, m
P_h	heated perimeter of the annulus, m
Pr	Prandtl number $(\mu C_p/k_f)$
q'''	volumetric heat generation rate, W/m^3
$\overline{r}$	dimensionless radial coordinate (r/r_i)
Re_D	Reynolds number $(\rho u_m D_h/\mu)$
s	specific entropy, J/kg K
S	entropy rate, W/K
St	Stanton number $(\overline{h}/\rho u_m C_p)$
T	temperature, K
T_w	wall temperature of solid core, K
u_m	mean fluid velocity, m/s
z	axial coordinate, m
$\overline{z}$	dimensionless radial coordinate (z/L)
ΔT	wall-to-bulk fluid temperature difference, K
ΔT_f	relative increase in fluid temperature, K
ΔT_{ref}	reference temperature difference $(q'''r_i^2/k_s)$, K

Greek symbols

δ	gap thickness, m
δ_C	temperature jump distance at gap–clad interface, m
δ_s	temperature jump distance at gap-fuel pin interface, m
λ	outer to inner diameter ratio of annulus (d_o/d_c)
μ	dynamic viscosity, Ns/m^2
ψ	length to hydraulic diameter ratio of the coolant channel (L/D_h)
π_1	dimensionless duty parameter $(\mu^{3/2}/\sqrt{32q'''}\rho r_i^2)$
ρ	density of coolant fluid, kg/m^3
τ	dimensionless wall heat flux $(\Delta T/T_{in})$

Subscripts

c	cladding
f	coolant fluid
g	fuel-clad gap
gen	generation
i	fuel pin surface
in	inlet
o	outer
s	solid fuel pin
w	fuel element outer surface

in course of flow. Many researchers worldwide studied the irreversibility patterns inside circular ducts and concentric passages taking into account of the variation of thermophysical properties. The characteristics of thermal and frictional irreversibilities for turbulent flow in a circular duct were analyzed by Bejan (1982,1995) from a thermodynamic viewpoint. It was shown in the analysis that beyond a critical Reynolds number the pressure drop characteristics dominate over thermal effects. Sahin (1998) analyzed irreversibilities in various duct geometries with constant wall heat flux and laminar flow. Circular geometry was concluded as the best, especially when the frictional contributions of entropy generation become substantial. Sahin (1999, 2002) took temperature dependence of viscosity into account and showed that viscosity variation might affect both entropy generation and the pumping power in certain cases. Nag and Kumar (1989) performed second law optimization for convective heat transfer through a duct with constant heat flux and analyzed the variation of entropy generation using a duty parameter. Oztop (2005) made a second law analysis in semicircular ducts in laminar region with constant heat flux. It was observed that cross sectional area has a determining role on entropy generation and with the reduction of the same, it increases. In the analysis performed by Jankowski (2009), the circular geometry was shown to be the best for adiabatic condition, while for high heat transfer irreversibilities, the geometry of one with large wetted perimeter was shown to be the best, based on minimization of entropy generation. Jarungthammachote (2010) showed the role of aspect ratio in a hexagonal duct on entropy generation. The studies of entropy generation of internal flow were also performed for the helical coil tube. Ko and Ting (2006) found the optimal flow rate as a function of coil curvature ratio and duty parameters. Mahmud and Fraser (2002) performed the second law analysis of an annulus with a rotary motion causing the convection of the fluid inside. They simplified the governing equations in cylindrical coordinates and used two different kind boundary conditions and made a second law analysis. The entropy generation was observed to be higher near inner cylinder and followed an asymptotic fall near the outer cylinder. Yilbias (2001) made an entropy analysis in concentric cylindrical annuli while the outer cylinder is rotating. The effects of Brinkman number on temperature and entropy generation characteristics were discussed elaborately. He considered entropy generation due to conduction, viscous dissipation and neglected fluid friction. The entropy generation due to flow and heat transfer of nanofluids in between co rotating cylinders with constant heat flux has derived by Mahian et al. (2012a) by solving the energy equation in cylindrical coordinates. They studied the effect of different parameters like velocity ratio; heat flux on inner cylinder on entropy generation has and obtained an optimal volume fraction of nano-particles that should be used for minimizing entropy generation. Mahian et al. (2012b) made a combined first and second law analysis to visualize the effects of MHD flow on velocity, temperature distribution and entropy generation between two concentric rotating cylinders which were essentially at different constant temperatures. The relative contributions of heat transfer, fluid friction and magnetic field in the average entropy generation have been found for six different cases. Also the optimum radius ratio minimizing entropy generation for any Hartmann number has been found to be 0.55.

The determination of analytical expressions for entropy generation in various components of a nuclear fuel element requires the knowledge of temperature variation within that component. The