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Entropy generation minimization (EGM) to optimize mass flow rate in dual channel cable-in-conduit conductors (CICCs) used for fusion grade magnets

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HIGHLIGHTS

- Entropy generation in CICCs is estimated using CFD.
- Entropy generation minimization technique is used to optimize the mass flow rate in CICCs.
- In dual channel CICC, contribution of thermal gradients to rate of entropy generation is higher as compared to contribution of velocity gradients.
- At a mass flow rate of 13 g/s, higher heat transfer rate and optimum pumping power is observed.
- The factors that affect entropy generation in CICCs are identified.

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ABSTRACT

Dual channel cable-in-conduit conductors (CICCs) used in tokamaks such as International Thermonuclear Experimental Reactor (ITER) consist of annular channel packed with superconducting strands and a clear central channel separated by a spiral from the annular channel. Supercritical helium (SHe) operating at 4.5 K and 0.5 MPa is used for forced convective cooling of CICC. Pressure drop is inevitable in the process of forced convective cooling, leading to the development of velocity gradients and temperature gradients. These velocity gradients and thermal gradients result in entropy generation in CICCs.

The present work aims at estimating volumetric rate of entropy generation (EG) in dual channel CICC. Subsequently, entropy generation minimization (EGM) technique is used to find optimum mass flow rate at which volumetric rate of EG is minimum. Pumping power and heat transfer corresponding to minimum rate of EG are also calculated. Computational fluid dynamics (CFD) is used as a tool to estimate EG as the analytical solution for turbulent forced convective flows requires inaccurate simplifications. A three dimensional model of dual channel CICC is developed in GAMBIT-2.1 and solved using a compatible solver FLUENT-6.3.26. The annular region of CICC is assumed to be porous and the central channel is assumed as clear region for EG analysis using CFD. The pressure gradients and heat transfer coefficient estimated from the simulations are validated against relevant experimental results available in the literature. The effect of mass flow rate on volumetric rate of EG in turbulent forced convective flow is studied using CFD.

1. Introduction

The concept of entropy generation minimization (EGM) is used in various engineering applications such as heat exchangers (HE), compressors and expansion devices to interpret the loss of thermodynamic efficiency [1,2] caused by irreversibilities. Entropy generation is evidenced in flow systems due to finite gradients in velocity and temperature [3]. Estimation of entropy generation entails an opportunity to optimize the geometrical parameters and operating parameters of a thermohydraulic system. In the large scale fusion energy applications such as tokamaks, thermohydraulic issues of cable-in-conduit conductors (CICC) were reported [4]. However, optimization of operating parameters of CICC using EGM method was not attempted. International Thermonuclear Experimental Reactor (ITER) is one of the tokomaks which employs

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Nomenclature

A_i	interface area between the fluid and solid phases (m^2)
C_F	Forchheimer coefficient
c_1, c_2	constants in Eq. (6)
c_k	constant
$\langle\overline{D}\rangle^v$	macroscopic deformation tensor, $\langle\overline{D}\rangle^v = 1/2\left\{\left[\nabla\left(\phi\langle\overline{u}\rangle^i\right)\right] + \left[\nabla\left(\phi\langle\overline{u}\rangle^i\right)\right]^T\right\}$
G^i	production rate of κ due to the porous material, $G^i = c_k\rho\varphi\langle\kappa\rangle^i\left\lvert\overline{u}_D\right\rvert/\sqrt{K}$ (kg/m s^3)
I	unit tensor
K	permeability (m^2)
n	normal component to the interface
$\langle\overline{p}\rangle^i$	intrinsic (fluid) average of pressure (Pa)
P^i	production rate of κ due to mean gradients of $\overline{u}_D$, $P^i = -\rho\langle\overline{u'u'}\rangle^i : \nabla\overline{u}_D$ (kg/m s^3)
$\langle\overline{T}_f\rangle^{i'}$	intrinsic average temperature of fluid (K)
$\langle\overline{T}_s\rangle^i$	intrinsic average temperature of solid (K)
$\overline{T}$	time averaged temperature (K)
$\overline{u}_D$	Dupuit–Forchheimer velocity (superficial velocity), $\overline{u}_D = \phi\langle\overline{u}\rangle^i$ (m/s)
$u_{D_{\parallel}}$	Darcy velocity component parallel to interface (m/s)
$\langle\overline{u}\rangle^i$	intrinsic average of time average of velocity vector $\overline{u}$ (m/s)
u'	fluctuation in velocity (m/s)
u, v, w	velocity components in x, y and z directions (m/s)
$\overline{u}, \overline{v}, \overline{w}$	time averaged velocity components in x, y and z directions (m/s)
W	width of the spiral rib (m)

Greek symbols

β	stress jump coefficient at interface
κ	turbulent kinetic energy per unit mass, $\kappa = \left[\overline{u}' \times \overline{u}'/2\right]$ (m^2/s^2)
$\langle\kappa\rangle^v$	volume (solid + fluid) average of κ (m^2/s^2)
$\langle\kappa\rangle^i$	intrinsic average (fluid) of κ (m^2/s^2)
μ	fluid dynamic viscosity (kg/m s)
μ_t	turbulent viscosity (kg/m s)
μ_{eff}	effective viscosity for porous medium, $\mu_{\text{eff}} = \mu/\phi$ (kg/m s)
$\mu_{t\phi}$	macroscopic turbulent viscosity, $\mu_{t_\phi} = \rho c_\mu\left(\langle k\rangle^{i2}/\langle\varepsilon\rangle^i\right)$ (kg/m s)
ε	dissipation rate of κ, $\varepsilon = \mu\left(\nabla u' : (\nabla u')^T\right)/\rho$ (m^2/s^3)
$\langle\varepsilon\rangle^i$	intrinsic average of ε, $\langle\varepsilon\rangle^i = \mu\left\langle\nabla\overline{u'} : (\nabla\overline{u'})^T\right\rangle^i/\rho$ (m^2/s^3)
ρ	density (kg/m^3)
ϕ	porosity
σ_k	Turbulent Prandtl number for κ
σ_ε	Turbulent Prandtl number for ε
λ_f	thermal conductivity of fluid (W/m K)
λ_s	thermal conductivity of strands (W/m K)
Ψ	viscous dissipation function

dual channel CICC [5–7] to cool the superconducting magnet. Fig. 1a shows such dual channel CICC used in TF (toroidal field) coil of ITER, containing an annular and a central channels and Fig. 1b shows a perspective view of longitudinal cross section. The annular porous channel of CICC contains individually wrapped six petals of twisted superconducting strands. The central clear channel is separated from the annular channel by a metallic spiral, thereby providing pressure relief to the flow of supercritical helium (SHe) coolant at ∼4.5 K and 0.5 MPa. Computational fluid dynamics (CFD) is one of the widely used tools for pressure drop and heat transfer analysis. An approach based on CFD using Reynolds-averaged Navier–Stokes (RANS) equations was proposed by Zanino, et al. [8] to overcome some of the difficulties involved in thermohydraulic studies of CICC. In our earlier work, we have developed a 3D model and estimated the pressure drop and heat transfer in CICC considering it as a partially filled porous medium [9]. It was also reported that the turbulence in the flow causes the occurrence of recirculation zones at leading and trailing edges of the spiral rib thereby initiating formation of eddies [10].

The transportation of eddies in the turbulent flow dissipate the energy termed as turbulent kinetic energy (TKE) resulting in temperature rise and pressure gradient [11]. Our earlier work reported that the thermal gradients develop due to transport of turbulence through CICC even without external heat sources [12]. Hence, entropy generation is expected due to development of gradients in velocity and temperature. As the measurement of entropy generation is not possible, analytical techniques are generally used to predict the entropy generation [13] with some compromise on accuracy in the solution. In order to counteract the simplification inaccuracies in the solution, iterative numerical methods and CFD were used to solve the governing equations of fluid flow and heat transfer [14,15]. Hence, it is necessary to estimate entropy generation in CICC using CFD, as the analytical solution is difficult for turbulent forced convective systems. Volumetric rate of entropy generation can be calculated if the velocity and temperature profiles are known at each and every point of the flow domain [2]. The effect of geometrical parameters on the pressure drop in dual channel CICC were investigated in the past [16] using computational fluid dynamics (CFD). In addition, optimization of geometrical parameters of single channel CICC was done using entropy generation minimization (EGM) method [17]. It is thus beneficial to estimate volumetric rate of entropy generation (EG) in dual channel CICC and use the results to optimize the operating parameters such as mass flow rate employing EGM method.

In the present work, motivated by the importance in evaluating entropy generation, we made an attempt to estimate the volumetric rate of EG in dual channel CICC using CFD. Thus calculated entropy generation is used to optimize the mass flow rate for efficient pumping of SHe through CICC used in fusion grade magnets. In addition, rate of heat transfer corresponding to minimum rate of entropy generation is estimated.

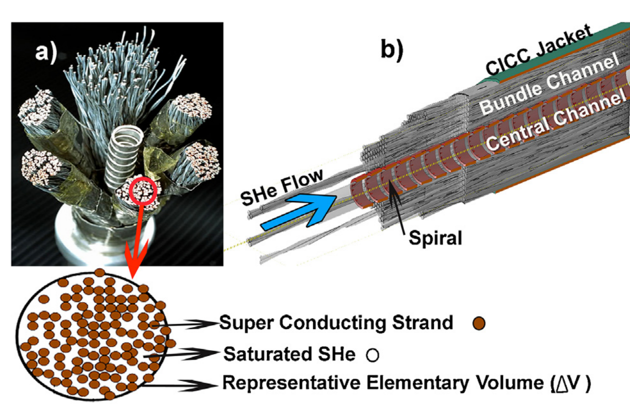

Fig. 1. (a) Dual channel CICC used in ITER TF-coil [4] (b) longitudinal cross section of CICC modeled using ABAQUS—perspective view.

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