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Influence of mass flow rate on Turbulent Kinetic Energy (TKE) distribution in Cable-in-Conduit Conductors (CICCs) used for fusion grade magnets

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HIGHLIGHTS

- Mechanism associated with turbulent flow in CICC is investigated using CFD.
- Reynolds Number (*Re*) affects the TKE in central channel but not that in bundle channel.
- The loss of TKE occurs at the interface between central and bundle channels.
- The loss of TKE is also observed as the flow progresses past the spiral rib.
- In the absence of external heat sources, loss of TKE leads to temperature rise of SHe.

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ABSTRACT

Thermohydraulic analysis is beneficial to understand the complex flow behavior in dual channel cable-in-conduit conductors (CICC) used in Tokomaks such as International Thermonuclear Experimental Reactor (ITER). Such dual channel CICC contains an annular and a central channel separated by a spiral. The cable bundle channel of CICC can be assumed to be porous and the central channel a clear region for thermohydraulic analysis using Computational Fluid Dynamics (CFD). Flow through CICC is found to be turbulent and this turbulence is transported in the form of small eddies. These eddies may dissipate the energy in the form of heat while being transported and finally the smaller eddies may combine to form larger eddy or may die out. Such phenomenon can be well explained with the help of a parameter called Turbulent Kinetic Energy (TKE), which determines the energy possessed by the eddies in the turbulent flow.

In the present work, 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 influence of mass flow rate on Turbulent Kinetic Energy (TKE), which is defined as the mean kinetic energy per unit mass associated with eddies in turbulent flow, is analyzed. The computational results of pressure drop and flow repartition are validated against relevant experimental published results.

1. Introduction

Cable-in-Conduit Conductors (CICC) used in International Thermonuclear Experimental Reactor (ITER) are considered as porous medium for pressure drop and heat transfer analyses using computational fluid dynamics (CFD) [1–3]. Fig. 1(a) shows such dual channel CICC used in TF (toroidal field) coil of ITER, containing bundle and central channel along with the representative elementary volume (REV), used here for the computational flow analysis. The bundle channel contains six petals of twisted superconducting strands individually wrapped. The central channel is delimited from the bundle channel by a metallic spiral, thereby providing a lower hydraulic impedance as well as pressure relief to the flow of supercritical helium (SHe) coolant at ~4.5 K and 0.5 MPa. Fig. 1(b) shows the longitudinal cross section of CICC along with the right side view of CICC. Friction factors (at different Reynolds numbers), which are a measure of pressure drop, and the effects of geometrical parameters on the pressure drop were investigated using computational fluid dynamics (CFD) in the past [4–7]. However, the increase in pressure drop in dual channel CICC was reported to be due to the development of recirculation zones adjacent to the spiral walls of CICC [8]. Although an approach based on CFD using Reynolds-Averaged Navier–Stokes (RANS) equations

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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
$(\bar{D})^v$	macroscopic deformation tensor, $(\bar{D})^v = 1/2\{[\nabla(\phi\langle\bar{u}\rangle^i)] + [\nabla(\phi\langle\bar{u}\rangle^i)]^T\}$
G^i	production rate of κ due to the porous material, $G^i = c_k\rho\varphi\langle\kappa\rangle^i\lvert\bar{u}_D\rvert/\sqrt{K}$ (kg/m s^3)
I	unit tensor
K	permeability (m^2)
$\langle\bar{p}\rangle^i$	intrinsic (fluid) average of pressure (Pa)
P^i	production rate of κ due to mean gradients of $\bar{u}_D$, $P^i = -\rho\langle\overline{u'u'}\rangle^i : \nabla\bar{u}_D$ (kg/m s^3)

Greek symbols

β	stress jump coefficient at interface
κ	turbulent kinetic energy per unit mass, $k = [\bar{u}'.\bar{u}'/2]$ (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, $\mu_{eff} = \mu/\phi$ (kg/m s)
$\mu_{t\phi}$	macroscopic turbulent viscosity, $\mu_{t_\phi} = \rho c_\mu\langle k\rangle^{i,2}/\langle\varepsilon\rangle^i$ (kg/m-s)
ε	dissipation rate of κ, $\varepsilon = \mu(\nabla u' : (\nabla u')^T)/\rho$ (m^2/s^3)
$\langle\varepsilon\rangle^i$	intrinsic average of ε, $\langle\varepsilon\rangle^i = \mu\langle\nabla\bar{u}' : (\nabla\bar{u}')^T\rangle^i/\rho$ (m^2/s^3)
ρ	density (kg.m^3)
ϕ	void fraction
η	normal component to the interface
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)
$\langle\bar{T}_f\rangle^{i'}$	intrinsic average temperature of fluid (K)
$\langle\bar{T}_s\rangle^i$	intrinsic average temperature of solid (K)
$\bar{u}_D$	Dupuit–Forchheimer velocity (superficial velocity, $\bar{u}_D = \phi\langle\bar{u}\rangle^i$ (m/s)
$u_{D\parallel}$	Darcy velocity component parallel to interface (m/s)
$\langle\bar{u}\rangle^i$	intrinsic average of time average of velocity vector $\bar{u}$ (m/s)
u'	fluctuation in velocity (m/s)
u, v, w	velocity components in x, y and z directions (m/s)
W	width of the spiral rib (m)

was proposed by *Zanino* et al. [4–7,9] to overcome some of the difficulties involved, the model was limited to two dimension in nature. The other reported computational thermohydraulic simulations were either one dimensional or two dimensional in nature, with 'time' as an extra dimension [10,11]. It is thus beneficial to develop a three dimensional spatial model using Computational Fluid Dynamics (CFD). Flow through CICC is found to be turbulent and this turbulence is transported in the form of small eddies. These eddies may dissipate the energy in the form of heat while being transported and finally the smaller eddies may combine to form larger eddy or may die out. Such phenomenon can be well explained with the help of a parameter called Turbulent Kinetic Energy (TKE), which determines the energy possessed by the eddies in the turbulent flow [12–14]. Further, transport of eddies in the turbulent flow results in increase of coolant temperature and rise in pressure gradient. Hence, accurate prediction of pressure gradient seems to be possible through the estimation of TKE in the flow. Motivated by these recommendations, we made an attempt to develop a complete 3D model in the present work, which is useful in estimating the effect of mass flow rate on turbulent kinetic energy in CICC used for fusion grade magnets.

2. Governing equations and boundary conditions

Modeling of CICC involves different transport phenomena such as electrical current, magnetic flux, mass, momentum, energy and turbulence. However, in this section, macroscopic governing equations applicable to steady, incompressible flow of supercritical helium (SHe) through CICC with mass, momentum, energy and turbulence transport are presented.

The present analysis is carried out for an incompressible, steady state, turbulent and three dimensional flow in CICC, which is partially filled by superconducting strands (porous medium) in the bundle channel, where the porous medium is saturated with single phase SHe. The porous material inside the CICC is considered homogeneous and anisotropic with a void fraction of 0.37 [9]. The supercritical helium enters the CICC at a constant mass flow rate (dm/dt) and at uniform temperature T_0. The temperature at the wall (jacket of CICC) 'T_w' is assumed to be constant. Furthermore, the variation of thermophysical properties of solid matrix (superconducting strands) with the temperature is not considered. Also gravitational effects, natural convection and thermal radiation heat transfer are all assumed to have negligible effect on the velocity and temperature fields. In addition, the SHe and solid superconducting strands are considered to be in local thermal equilibrium. The governing equations are based on one domain approach (for both the central and bundle channel of CICC) and with the above assumptions take the form as follows:

2.1. Macroscopic governing equations

The time averaged RANS equations are volume averaged in REV to obtain macroscopic transport equations applicable to flow through CICC. The conservation of mass in REV can be written as[13]:

$$\nabla\cdot(\rho\bar{u}_D) = 0 \tag{1}$$

where $\overline{u}_D$ is the Dupuit–Forchheimer velocity (superficial velocity) in the REV, $\overline{u}_D = \phi\langle\overline{u}\rangle^i$, and $\langle\overline{u}\rangle^i$ is the intrinsic average of the local time average of velocity vector $\overline{u}$. The macroscopic momentum transport equation applicable for steady flow through CICC considering the inertial and form drag is given by:

$$\nabla\cdot\left(\frac{\rho\overline{u}_D\overline{u}_D}{\phi}\right) = -\nabla\cdot(\phi\langle\overline{p}\rangle^i) + \mu\nabla^2\overline{u}_D + \nabla\cdot(-\rho\phi\langle\overline{u'u'}\rangle^i)$$
$$-\left[\frac{\mu\phi}{K}\overline{u}_D + \frac{C_F\rho\phi\lvert\overline{u}_D\rvert\overline{u}_D}{\sqrt{K}}\right] \tag{2}$$

where μ is the fluid dynamic viscosity, u' is fluctuation in velocity, K is the permeability of the porous medium, C_F is known as the quadratic Forchheimer coefficient (drag coefficient) and the term $-\rho\phi\langle\overline{u'u'}\rangle^i$ is the macroscopic Reynolds stress tensor given by

$$-\rho\phi\langle\overline{u'u'}\rangle^i = \mu_{t_\phi}2(\overline{D})^v - \frac{2}{3}\rho\phi < \kappa >^i I$$

where $(\overline{D})^v = (1/2)\{[\nabla(\phi\langle\overline{u}\rangle^i)] + [\nabla(\phi\langle\overline{u}\rangle^i)]^T\}$ is the macroscopic (volume averaged) deformation tensor, $\langle\kappa\rangle^i$ is the intrinsic average