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Simulation of the flow-reversal effect in dual-channel CICC for ITER

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Abstract

The discovery of an upward counter flow of helium in the outer annulus of the vertically oriented and top-to-bottom cooled ITER PF-FSJS (Poloidal Field Coil-Full Size Joint Sample) in 2002 led to closer investigations of the effect because it may lead to a reduction of the operational margin of the superconductor used in the ITER environment. Recently, further thermo-hydraulic experiments were carried out on the TFAS2 sample (Toroidal Field Advanced Strand sample 2) with the intent to asses the effect in detail. First investigations confirmed the initial assumption that the origin of the effect lies in the buoyancy of the heated, and thus less dense, helium in the outer annulus of the cable. The helium there is in good contact with the superconducting strands heated by neutron irradiation, ac losses or heat influx, but is thermally and hydraulically less well coupled to the downward flowing helium in the central channel. This paper presents an analysis of the TFAS2 experiments using the simulation program THEA™, specifically extended with a term for gravitational forces acting on helium of varying density. With the experience gained, the simulation of the thermo-hydraulic behavior of the Toroidal Field Coil inner leg shows the operational limits and boundary conditions of this coil in ITER.

Keywords: Heat transfer; Cable in conduit conductors; Supercritical helium; Fusion magnets

1. Introduction

The dual-channel cable-in-conduit conductors (CICCs) developed for the ITER high field coils have a number of advantages over single-channel CICCs: the lower pressure gradient along the cable allows designs with longer cable sections between helium supply ports, the additional helium flow reduces the temperature increase between helium inlets and outlets, and during a cable quench the central channel serves as a high-capacity escape route for the warmed-up helium, thereby limiting the local pressure increase. The major disadvantage of dual-channel CICCs is the difficulty in assuring sufficient helium flow in the channel containing the superconducting strands to provide the required cooling under all circumstances. Experiments on the ITER PF-FSJS full size conductor sample in 2002 [1–3] led to the discovery of a configuration where the flow in this channel stagnates and even reverses. This effect is closely related to the strong reduction of the helium density with increasing temperature at usual operating conditions ($T \sim 4.5$ K, $p \sim 5$–10×10^5 Pa): helium in zones with reduced density experiences an upward buoyancy force from the surrounding, denser helium. The phenomenon is usually called flow-reversal effect, the details of which are further discussed in Section 2. Because of its thermo-hydraulic origin, it has also been named thermosyphon effect [4].

The detailed thermo-hydraulic data recently measured on the TFAS2 sample in SULTAN (Section 3) provided the reference for the interpretation and benchmarking of simulations of the flow-reversal effect with the computer program THEA (Section 5). For this purpose, THEA, the well established and validated cryogenic simulation program, was enhanced to take account of gravity forces on helium. The measurement results also motivated an analytical estimation of the power required for the onset

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of the flow-reversal effect, outlined in Section 4. The potential impact of the flow-reversal effect on the operation of the ITER toroidal field coils is finally addressed in Section 6.

2. The flow-reversal effect in dual-channel CICCs

In a vertically oriented cable segment with a typical helium flow rate (e.g. 10 g/s) the hydrostatic pressure gradient is much larger than the pressure drop caused by friction. Downward flowing helium thus flows against the pressure gradient. Because a spiral with a high perforation fraction separates 'bundle' (the annular channel containing the superconducting strands) and 'hole' (the central channel containing only helium), the pressure – and pressure gradient – is nearly the same in both channels at every point along the cable (see Fig. 1). With no external heat load, also the temperature and the helium density are the same in bundle and hole at every elevation. The partition of the helium flow among bundle and hole thus depends only on the friction forces in the two channels and is constant along the conductor (apart from some possible redistribution close to the helium inlet).

A significant part of the vertically oriented conductors forming the ITER toroidal field coils, however, experiences heat loads originating from AC losses in the conductor, nuclear heating, and heat influx by thermal radiation and conduction [5]. In some of these conductors, helium flows downwards. This external heat influx and corresponding temperature increase cause the helium density in the bundle to decrease, and the gravitational pressures of the helium columns in bundle and hole do not balance any more. Since both channels are still closely coupled hydraulically, the

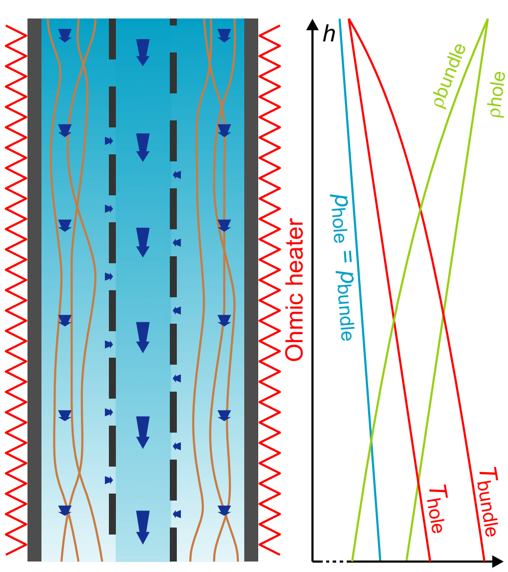

Fig. 1. Schematic drawing of a dual-channel CICC with helium flowing downward and exposed to an external heat load. The graphs on the right qualitatively show the distribution of pressure, temperature and density along the conductor for the hole as well as for the bundle.

change in gravitational pressure gradient is compensated by a corresponding change in the pressure drop originating from friction: the less dense helium in the bundle slows down and the denser one in the hole accelerates. Although the pressure differences between channel and hole are very small, they generate important transverse (bundle ↔ hole) mass flows because of the very small hydraulic impedance between the two channels.

The equation describing the change of momentum ($\Delta p = F\Delta t$) for the helium in a channel element of height Δh in time Δt on which a total force F acts, is

$$\frac{\partial \dot{m}}{\partial t}\Delta h\Delta t = \frac{\partial(\rho A v)}{\partial t}\Delta h\Delta t = \left(-\frac{\partial(\rho A v^2)}{\partial h} - \frac{\partial(pA)}{\partial h} - \frac{-2f\rho A v|v|}{D} - g\rho A + \bar{v}\frac{\partial(\rho A v)}{\partial h}\right)\Delta h\Delta t, \quad (1)$$

where $\dot{m}$ is the mass flow, A is the channel cross section, ρ the helium density, p the pressure, f the friction factor, D the hydraulic diameter, g the gravitational constant and $\bar{v}$ the helium velocity in the channel from which helium leaves to the other channel. In the stationary case, which is interesting because it describes the salient features of the flow-reversal effect, the left side is zero and the equation becomes one of force balance. The five terms in the bracket are in turn: the net momentum transfer with the helium flow along the channel, the net force from the pressure at the element's ends, the friction force, the gravitational force and the net momentum transfer from the transverse mass flow. In the last term the mass conservation law is used to calculate the transverse mass flow rate per unit length $\dot{m}'_{12} = \partial\dot{m}/\partial h$, which is only possible in a two channel problem.[1]

Under the conditions studied, the five terms have significantly different magnitudes: the gravitational force is by far the largest term (~1400 Pa/m per cross section and unit length), which is balanced by the hydrostatic part of the pressure gradient. Although the flow velocities change substantially and even change direction, the friction term reaches at most about a tenth of the gravitational term. As described above, it balances variations in the gravitational force caused by density variations. The remaining two terms are again about a tenth smaller and can be neglected for a first analysis.

3. Thermo-hydraulic measurements on TFAS2

In addition to measurements of the current sharing temperature and other electrical parameters as a function of applied field [6], the TFAS2 sample offered the opportunity to study the flow-reversal effect in detail. For this purpose, both legs were equipped with dedicated heaters and additional voltage taps and the helium flow was reversed to top-to-bottom. Fig. 2 shows a picture and the layout of

[1] In the simulation this term is calculated iteratively as a function of the pressure difference between the two channels.