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CRYOGENIC ANALYTICAL TOOLS FOR LHe DISTRIBUTION DESIGN

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CRYOGENIC ANALYTICAL TOOLS FOR THE
LHe DISTRIBUTION SYSTEM DESIGN*

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INTRODUCTION

The helium cooled superconducting magnets depend on computer simulation to accurately analyze their various fluid systems. Traditional closed-form analytical solutions generally have limited validity due to restrictive simplifying assumptions. Experimental methods are additional design process techniques used in analyzing complex systems. Experimental testing has several disadvantages such as economics, time, and difficulty in achieving exact operating conditions. Computational or numerical methods in the form of computer algorithms provide an extremely advantageous method of analytical solutions. These tools offer the advantages of economics, speed, flexibility, and accuracy. Two such tools for analyzing cryogenic fluid systems of superconducting magnets were developed by the thermodynamics group of General Dynamics/Convair.

The cryogenic distribution systems for large superconducting magnets can make practical use of natural convection to provide helium circulation. Unlike a forced flow system which has external means of controlling the flow rate, a natural convection system has very little flexibility to change the flow parameters once the magnet system is operating. Because of the lack of flexibility, a rigorous design of the fluid distribution system is extremely important. To support the sizing of the helium lines and to provide a simulation of the circulation system, a finite differencing computer program, "THERMOSIPHON", was written.

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During various fault conditions, the pressure and flow rate of the liquid helium in the magnet cryostat can suddenly rise due to heat addition. An earlier GDC computer program was revised and optimized for use in modeling the thermodynamic properties of helium during an emergency discharge condition. This revised program, "MAGPRS", calculates the transient conditions within the cryostat as well as the "quasi-steady state" vent line conditions for each time step.

These two analytical tools are presently being utilized to determine the helium distribution and quench pressure relief system requirements for the Mirror Fusion Test Facility 26-magnet system at Lawrence Livermore National Laboratory.

THERMOSIPHON COMPUTER PROGRAM

Purpose

In addition to keeping the magnet winding below the critical temperature of the superconductor, the helium must have a sufficiently low volumetric vapor quality (i.e., void fraction) to maintain cryostability. Accumulation of vapor bubbles can cause an area of poor helium heat transfer due to a "drying out" region. To prevent excessive exit qualities in the winding pack, the flow must be sufficient to attenuate specific enthalpic increases. For an established heat input, an increase in flow rate (and a reduction in exit quality) can be obtained by reducing the overall impedance of the distribution system. The sizing of the distribution system becomes the most significant task for assuring an adequate cryogenic system for the magnet.

Theory

A liquid natural circulation system operates by thermosiphon principles. Heat input to the closed helium loop creates density and buoyancy gradients in the flow circuit. The initial pressure head is maintained by locating the helium supply dewar above the superconducting magnet. With the onset of heat generation, thermosiphonic flow commences. The natural circulation is self-sustained by this internal forcing function if there is continuous heat input and liquid helium supply.

Opposing the helium flow driver elements are the resistive elements in the form of head loss components. These head losses or flow impedances are due to friction, elevation and momentum.

The frictional loss component is very sensitive to distribution line sizes. Analytical equations are readily available for pipe flow friction coefficients. Uncertainty develops when analytical or assumed model empirical correlations are used to determine friction parameters within the magnet winding flow area. To aid in the formulation of accurate frictional data, Lawrence Livermore National Laboratory performed a pressure/flow test on the MFTF-A Yin-Yang magnet thus establishing a valuable friction correlation for winding packs of a similar nature.¹ An additional correlation was developed in the same way by GDC for the MFTF-B solenoid magnet which has different internal characteristics.² Depending on the helium heat input, a portion of the flow circuit may have two-phase flow conditions. This condition will create additional friction pressure drop due to the liquid and vapor phases having different velocities (i.e., slip flow). The Baroczy correlation provides a two-phase frictional multiplier for this slip flow model.

The elevation or gravity pressure component is directly a function of dewar height and is a significant parameter affecting the mass flow rate and the helium state.

The momentum component contributes minor pressure differentials due to area and density changes throughout the flow circuit. Since the typical piping elements utilized at flow passage area expansions do not act as efficient diffusers for the liquid phase, momentum recovery is assumed to be negligible.

By solving the basic energy, momentum, and continuity equations, the flow rate and thermodynamic conditions can be established for the entire system.

Governing Physical Equations

Energy Equation:

$$\dot{Q} + \dot{W}_{\text{net}} = \dot{m} \int_{\text{c.s.}} (h + v^2/2g_c + gz/g_c) \quad (1)$$

$$\dot{Q} = \dot{m}(h_2 - h_1)$$

Momentum Equation:

$$dp + \frac{\rho g dz}{g_c} + \frac{\rho d(v^2)}{g_c} + \frac{\rho v^2}{2g_c} (\phi^2 f \frac{dx}{D_H} + \phi C_D) = 0 \quad (2)$$

Continuity Equation:

$$\dot{m} = \rho A v \quad (3)$$

Thermodynamic State:

$$\rho = \rho(h, p) \quad (4)$$

Exit Quality:

$$x = \frac{h - h_f}{h_{fg}} \quad (5)$$

Parallel Flow Formulation

Mass Balance:

$$\dot{m} = \dot{m}_A + \dot{m}_B + \dots + \dot{m}_n = \sum_{i=A}^n \dot{m}_i \quad (6)$$

Equivalent Pressure Drop

$$\Delta P = \Delta P_A = \Delta P_B = \dots = \Delta P_n = k \dot{m}^2 = k_A \dot{m}_A^2 = k_B \dot{m}_B^2 = \dots = k_n \dot{m}_n^2 \quad (7)$$

$$\text{where, } k_i = \left(\phi^2 f \frac{\ell}{D_h} + \phi_k C_D \right) \frac{1}{2A^2 \rho g_c}$$

Combine 6 & 7

$$(1/k)^{1/2} = (1/k_A)^{1/2} + (1/k_B)^{1/2} + \dots + (1/k_n)^{1/2} = \sum_{i=A}^n (1/k_i)^{1/2} \quad (8)$$

$$\dot{m}_i = (k/k_i)^{1/2} \dot{m} \quad (9)$$

Nomenclature:

$\dot{Q}$ = heat rate

$\dot{m}$ = flow rate

h = enthalpy

p = pressure

ρ = density

v = velocity

ℓ = length

D_h = hydraulic diameter

C_D = specific flow losses

g = gravitational acceleration

g_c = proportionality constant

x = exit quality

A = flow area

f = Darcy friction factor

z = elevation

Computer Algorithm

A computer program solves the governing flow equations and the parallel flow distribution equations for a steady state generalized flow situation. The program consists of one main program and four supporting subroutines. The real properties of helium are simultaneously computed from the NBS computer program.³

The main program, "SIPHON", uses an assumed flow rate for the finite differencing of the pressure drops throughout the flow circuit. Since most systems consist of multiple branch flow circuits, the portion of flow to each branch must be determined. Through the use of an internal iterating technique that generates head loss coefficients, the flow distribution is determined for the network. Before the branches converge into a common line, a mixing process must take place to determine the new properties of the homogeneous mixture. The mixing process with heat exchange is simulated with two control volumes (Figure 1). Control volume ABCD is non-mixing and non-isobaric with heat exchange, while control volume BCDE is adiabatic, isobaric mixing.

Figure 1. Mixing Control Volumes for Multiple Branches

Energy Balance:

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 + \dot{m}_3 h_3 + \dot{Q}_1 + \dot{Q}_2 + \dot{Q}_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2 + \dot{m}_3 h_3 \quad (10)$$

Mass Balance:

$$\dot{m}_1 + \dot{m}_2 + \dot{m}_3 = \dot{m} \quad (11)$$

Pressure Equality:

$$P_1' = P_2' = P_3' = P$$

Derived Enthalpy and Quality of Mixture:

$$\frac{\dot{m}_1 h_1' + \dot{m}_2 h_2' + \dot{m}_3 h_3'}{\dot{m}} = h \quad (12)$$

$$\frac{h - h_f(P)}{h_{fg}(P)} = X \quad (13)$$

Once the flow distribution is determined through the parallel branches, then the remaining pressure potentials are determined at the downstream nodes. Since the nodal structure for the flow network uses a closed circuit, the final pressure is compared with the initial pressure. The pressure imbalance resulting from the initial flow rate is used to predict a new flow rate based on the Newton-Raphson iteration technique.

The subroutine, "PROPS", finds the new temperature, pressure, density, and quality based on the assumed mass flow rate and the known enthalpy. The pressure is found by solving the individual pressure drop components which consist of frictional, momentum and elevation contributions. All of the components are a function of the unknown density which in turn is a function of the new pressure. An internal iteration process is used to obtain total agreement for the properties.

If the thermodynamic state is in the two-phase region, the subroutine, "SAT", is used to determine the saturated properties from the helium library subroutine. A single phase fluid would obtain its properties similarly from a subroutine, "SUPSUB".

The subroutine, "FRICK", offers four choices of friction equations and a two-phase pressure drop correlation. The piping elements obtain their friction coefficients from either the smooth pipe formula or Colebrook's generalized friction equation (i.e., Moody Diagram). The magnet flow regions utilize either the LLNL or the GDC empirical friction correlation depending on the winding pack configuration. The two phase multiplier, ϕ^2 , is determined from the Baroczy

correlation.⁴ It is multiplied by the friction factor to obtain two-phase pressure drop.

$$\phi^2 = \left[1 + \frac{c}{x_{tt}} + \frac{1}{x_t^2} \right] (1 - x)^{1.8} \quad (10)$$

where:

$$c = -2.0 + (28. - .3G) \exp \left(\frac{-(\log_{10} \Lambda + 2.5)^2}{2.4 - 10^{-4}G} \right)$$

$$\Lambda = \left(\frac{\mu_f}{\mu_g} \right)^{.2} \left(\frac{\rho_g}{\rho_f} \right)$$

$$x_{tt} = \Lambda^{1/2} \left[\frac{1 - x}{x} \right]^{.9}$$

μ = viscosity

G = mass flux (lbm/hr-ft² for above equation)

Since it has been found that local losses tend to homogenize the flow, the appropriate local loss two-phase multiplier is the homogenous multiplier, ϕ_k .

$$\phi_k = 1 + \frac{v_g - v_f}{v_f} x \quad (11)$$

v = specific volume

This term is then multiplied by the local loss term, C_D , in the frictional pressure drop equation.

Although the program was designed primarily for natural flow analysis, it also has the capability of analyzing forced or forced/natural systems. A compressor or pump is simulated by adding the equivalent pressure rise to the circuit input.

A simplified logic flow diagram, Figure 1, outlines the basic structure of the algorithm.

Convective Flow Analysis

"THERMOSIPHON" was used to analyze the various magnet system configurations on MFT-B. The nodalization of one such system is shown in Figure 3, along with the analytical results of this analysis in Figure 4. The Solenoid system requires

1.5 inch supply lines to produce a steady state flow rate of 75 g/sec. The steady state exit quality at the top of the magnet is 1.01 wt. % and increases to a peak of 2.39 wt. % during the transient condition. This system was designed to a conservative limit of 2.5 wt. % in order to assure cryostability at all times.

QUENCH PRESSURE COMPUTER PROGRAM

Purpose

The complex vent systems used on large superconducting magnets require accurate modeling of the cryostat and fluid lines during an emergency discharge condition. This analysis requires computer simulation through the use of a generalized flow computer code. It is extremely important to monitor the pressure rise and helium discharge during this simulation. This information can then be used to design the vent line system within the criteria for maximum pressure and flow allowables.

A previously GDC computer code⁵ was rewritten to overcome its inherent execution problems and to extend its capability.

Theory

During design operating conditions with the magnet in its superconducting mode and contained within a vacuum, very little energy is deposited in the liquid helium cryostat. During a magnet quench (i.e., rapid normalization of the superconductor accompanied by large increases in ohmic heating) or a loss of vacuum conditions, a significant rate of energy deposition to the helium could occur.

A basic thermodynamic model that calculates the internal energy and specific volume changes can be used to obtain the pressures and temperatures of the helium in the cryostat. Once the pressure relief system is activated, helium discharge is initiated. The onset of fluid flow requires the solution of the partial differential equations which consist of area changes of the vent line, heat transfer into the fluid flow, and variable friction parameters. The compressibility effects along with the condition of choked flow must also be imposed on the generalized vent equations. Although the actual flow conditions are unsteady, a "quasi-steady state" model that uses equations 1-5 will accurately simulate the system by using an implicit finite differencing method. The governing thermodynamic vent line flow equations, along with the parallel flow

formulation are essentially the same as the thermosiphon derivations.

Quench Pressure Analysis

All of the magnet groups of MFTF-B were analyzed with "MAGPRS". This system requires a 2 inch vent line from each magnet and a 3 inch common return for the pair. A pressure relief valve is activated when the cryostat pressure reaches 5 atm. The criteria for vent line sizing requires the magnet pressure to be limited to approximately 7 atm. The results of the solenoid system are shown in Figure 5.

Figure 5. Solenoid pressure, temperature and mass during quench

CONCLUSION

The two computer programs presented in this paper are both fundamentally general in that they could be applied to other magnet systems. In addition to MFTF-B analyses, these programs will be used on current and future GDC superconducting magnet projects. Future extended capabilities will include transient heating and flow conditions for "THERMOSIPHON" and multiple magnet quench features for "MAGPRS".

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FIGURE I. MIXING CONTROL VOLUMES FOR MULTIPLE BRANCHES.

THERMOSIPHON

FIGURE 2. Logic flow diagram for "THERMOSIPHON".

FIGURE 3. NODALIZATION OF MFTF-B SOLENOID MODULE FOR THERMOSIPHON ANALYSIS.

Figure 4. Helium properties in flow circuit during solenoid steady state operating conditions

Figure 4. Helium properties in flow circuit during solenoid steady state operating conditions.

Figure 5. Solenoid pressure, temperature, and mass during quench