Water Cooling of RF Structures

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Abstract

We present computer codes for heat transfer in water cooled rf cavities. RF parameters obtained by SUPER-FISH or analytically are operated on by a set of codes using PLOTDATA, a command-driven program developed and distributed by TRIUMF [1]. Emphasis is on practical solutions with designer's interactive input during the computations. Results presented in summary printouts and graphs include the temperature, flow, and pressure data.

1 INTRODUCTION

The design of a cooling system for a rf cavity is a multidisciplinary task, usually carried out by a reluctant rf physicist, a mechanical engineer or both. They have two kinds of tools to use: sophisticated finite element programs with elaborate inputs and long CPU times, or the classical ways of cooling/heating specialists. In most cases they both first have to learn how to understand each other. The work presented is an attempt to bridge the gap, and offer a set of programs with simple input/output files which provide results within seconds or minutes. One program is written in Basic, the rest employs PLOTDATA, which is now used at a number of accelerator laboratories. Its main advantages are transparent programming and superior graphics capability. In some of the programs simplifying assumptions are made; in all cases conservative solutions are obtained.

2 PROBLEM DESCRIPTION

2.1 Heat generation

It is assumed that the magnetic component of the rf field on the cavity walls (or wall currents) is known. We have found SUPERFISH most useful since its output directly contains most of the cavity parameters (geometry, frequency, Q, total power) as well as a file $i = i(r, z)$ for individual segments. Cases with circular and cylindrical segments are then solved by editing the file OUTSFO.LIS and operating on it as shown in the flow chart. When a SUPERFISH solution is not available, an input file of the same format must be generated otherwise.

2.2 Heat transfer

The problem is described in three parts (see Fig. 1):
  Conduction between two heat sinks ($T_{max} \rightarrow T_{sink}$)
  Cavity segments are generally of three basic types, which can be dealt with as follows:

- cylindrical; rf surface is developed into a rectangle with parallel heat sinks; 1-D problem in rectangular coordinates

- annular disks with circular heat sinks; 1-D in polar coordinates

- planar geometry; a 1-D model can be used by dividing area into rectangular sections enclosed by straight heat sinks and by the summation of individual sections.

One dimensional cases in both coordinate systems are treated in Ref. [2]. where details of electric heat generation and conduction are given. Included is a discussion on approximate solutions and their accuracy, and a method of determining the spacing between heat sinks in a 1-D array such that the local maxima are equal.

2.3 Forced convection ($T_{sink} \rightarrow T_b$)

Newton's equation for forced convection heat transfer takes a deceivingly simple form $q = hA(T_w - T_b)$ where A is the surface area. T_w and T_b are the wall and bulk temperatures and the problem is in determining the heat transfer coefficient h. Exact theoretical solutions do not exist but empirical formulae are generally used with good results. It is beyond the scope of this paper to reproduce sections of handbooks on forced convection heat transfer. A solution for this case can be obtained by assuming that the half-tube section is a longitudinal fin of rectangular profile with a developed length L. A standard formula for the temperature difference ($T_{sink} - T_b$) can be used (Ref. [3]).

2.4 Incremental change in bulk temperature T_b

This increase is taken from the energy balance in the interval. In the programs for cylinders, disks and annuli the temperature T_b is considered constant for each heat sink, and the point of maximum temperature is postulated to be halfway between the ducts. In cases with planar geometry T_b is incremented in several small steps along the entire length of the duct, and the location of T_{max} is found exactly ("continental divide").
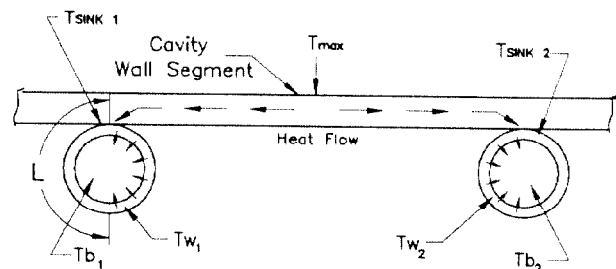

Fig. 1. Schematic of heat flow.

2.5 Water flow in ducts

The water in the cooling ducts must be supplied to the cavity in sufficient quantity at a given temperature and within an acceptable pressure range. The flow rate is computed from the energy balance for the cavity segment, and it determines the sizing of the cooling ducts, which in turn affect the conduction in the segment through changes of geometry and temperatures at the sinks.

2.6 Pressure differentials

Computing of pressure drops in cooling ducts is again based on standard empirical formulae. In the programs corrections are taken for changes in water properties as a function of temperature (viscosity, specific heat etc.). Increase in friction factors for curved ducts (helical coils, spirals and bends) is also taken into account, while effects of elbows and tees are expressed as additional effective lengths.

3   1D PROBLEMS*

(see Fig. 2.)

3.1   Generate/edit SEG.IN (A,D)

- frequency and total power from OUTSFO.LIS
- chosen inlet/outlet temperature of the cooling water
- chosen maximum desired temperature in segment
- segment wall thickness (gauge)
- anticipated reduction in Q for cavity as built
- estimated coefficient for reduction of cooling channel spacing due to $T_{sink} \to T_b$
- correct name of SEG*.FILE

check SEG.OUT for excessive flow
Note: for historical reasons SEG.IN is a dual purpose file; all other execution files are named RUN.

3.2   Generate/edit SINK.IN (B,E)

- inlet/outlet water temperature from SEG.IN
- flow from SEG.OUT
- chosen dimensions of round/flattened tubing; if rectangular channel, FRACTION corrects for special cases.
- selected flow direction; positive sign → increasing z coordinate; 0 → double helix
- locations of heat sinks chosen from SEG.OUT

check SINK.OUT for maximum segment temperature

3.3   Generate/edit COIL.IN (C,F)

- inlet/outlet water temperature and flow same as SINK.IN
- diameter of cooling coil
- 3 hydraulic diameters of tubing (0 is a valid entry)
- coil turn spacings same as SINK.IN

check COIL.OUT for excessive pressure/velocity
Note: if coil cooling duct and/or segment wall thickness require corrections, changes have to be made in the SINK/SEG input files.

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*description is worded for rectangular coordinates; for discs file names have a prefix RAD except for COIL, where the corresponding file is SPIRAL.
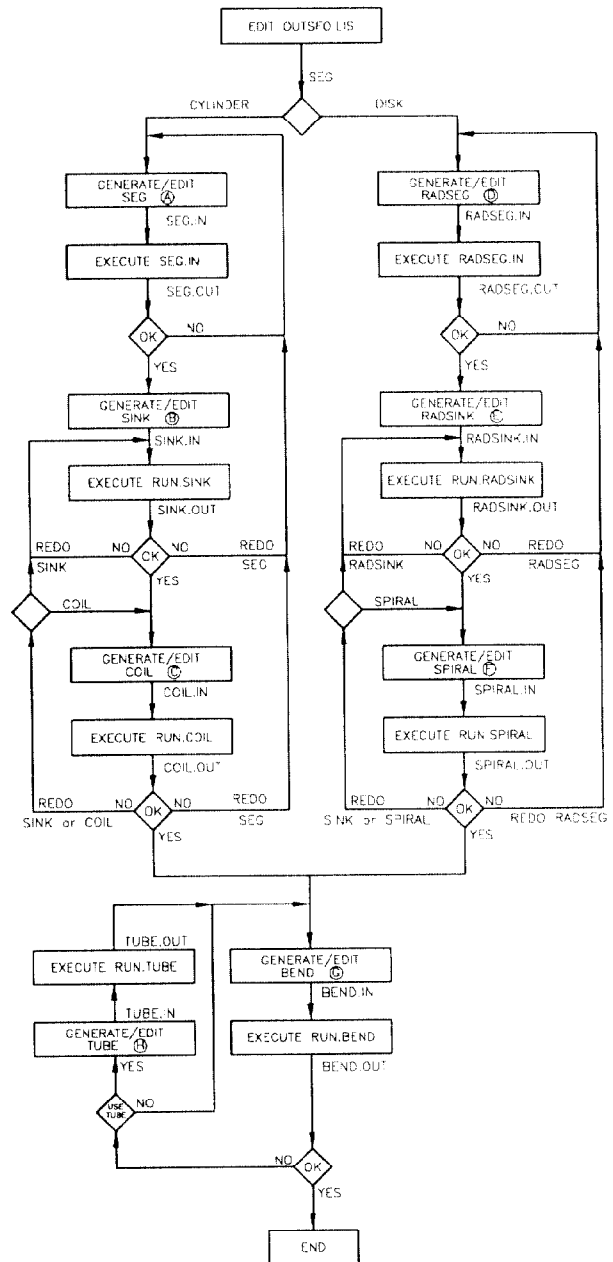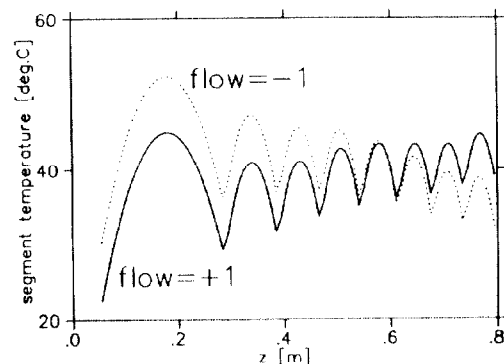

Fig. 2. Flow chart for 1-D problems.

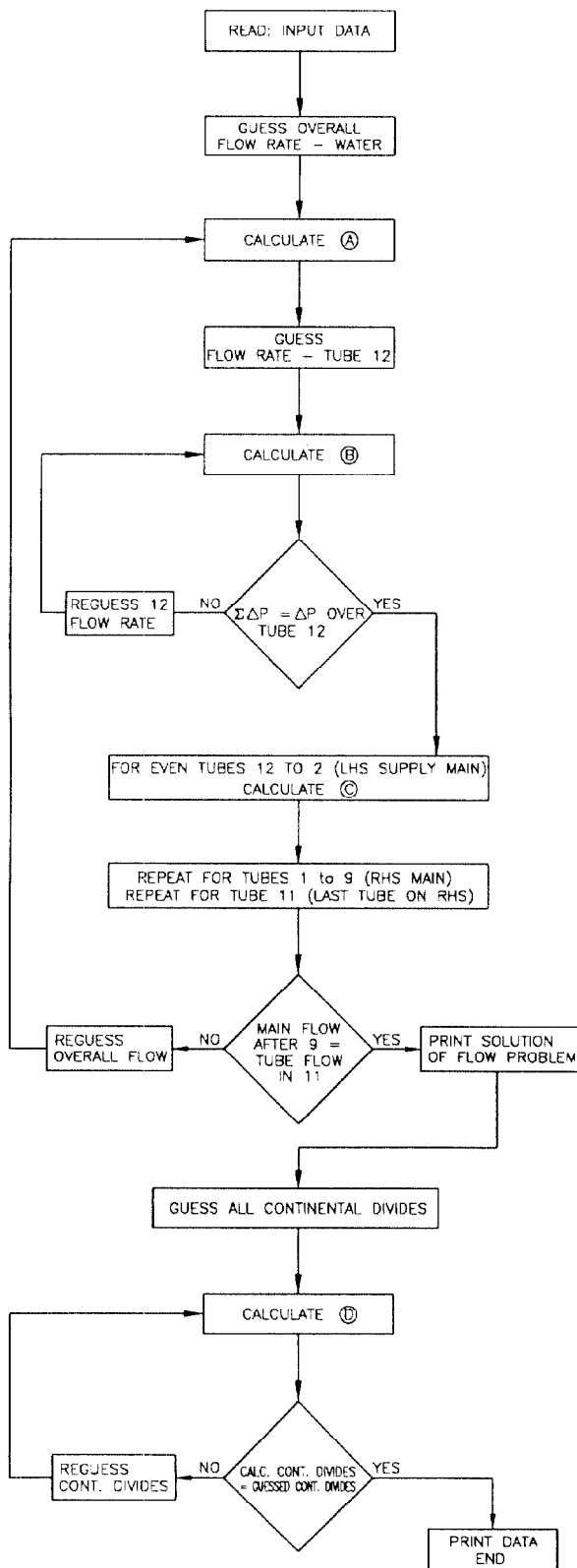Fig. 3. Example of flow reversal.

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Fig. 4. Flow chart for planar problems.

The flow chart text contains:

- READ: INPUT DATA
- GUESS OVERALL FLOW RATE – WATER
- CALCULATE Ⓐ
- GUESS FLOW RATE – TUBE 12
- CALCULATE Ⓑ
- REGUESS 12 FLOW RATE — NO — ΣΔP = ΔP OVER TUBE 12 — YES
- FOR EVEN TUBES 12 TO 2 (LHS SUPPLY MAIN) CALCULATE Ⓒ
- REPEAT FOR TUBES 1 to 9 (RHS MAIN) REPEAT FOR TUBE 11 (LAST TUBE ON RHS)
- REGUESS OVERALL FLOW — NO — MAIN FLOW AFTER 9 = TUBE FLOW IN 11 — YES — PRINT SOLUTION OF FLOW PROBLEM
- GUESS ALL CONTINENTAL DIVIDES
- CALCULATE Ⓓ
- REGUESS CONT. DIVIDES — NO — CALC. CONT. DIVIDES = GUESSED CONT. DIVIDES — YES
- PRINT DATA END

3.4 Process TUBE (H)

Designed to help select the cooling duct parameters.
Generate/edit TUBE.IN

- inlet/outlet water temperature and flow
- minimum/increment of/maximum HD of choice
- total effective length from COIL/SPIRAL

check graph and TUBE.OUT

3.5 Manifolds

When all design parameters satisfied, cooling manifolds consisting of straight sections, elbows and bends will be added to the structure. Constant hydraulic diameter is assumed.
Generate/edit BEND.IN

- flow, hydraulic diameter and total length of straight runs
- inlet/outlet water temperature
- number and type of elbows, tees and bends

obtain BEND.OUT

4 PLANAR PROBLEMS [4]

The flow chart for a solved case (60 kW skin loss in a flat electrode) is shown in Fig. 4.
Input data: inlet water temperature
2-D tube array layout
tube sizing
chosen pressure difference
A,B,C: Hydrodynamic calculations
D: Thermodynamic calculations, obtain continental divides

Output data: outlet water temperature
segment maximum temperature
incremental sink temperatures
The results were verified by direct temperature measurements on the rf cavity and found to be within several percent. The frequency stability of the resonator is extremely high.

5 REFERENCES

[1] J.L. Chuma, TRI–CD–87–03; (TRIUMF Internal Note).

[2] M. Zach, TRI–DN–86–41; (TRIUMF Internal Note).

[3] J.P. Holman; Heat Transfer, McGraw-Hill, (1981).

[4] G. Battersby, TRI–DN–86–20; (TRIUMF Internal Note).