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Modeling of He II Two-Phase Flow for the TESLA 500 Cryogenic Systems

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Abstract

The TESLA 500 cooling system uses He II two–phase flow to supply the saturated He baths containing the superconducting cavities. This flow must operate in a predictable manner for proper linac operation. This report discusses the procedure for modeling the flow. The He II system of TESLA 500 is described and the likely two–phase flow regimes are discussed. From this information, a basic mathematical model of the flow is introduced. Future experiments using the TESLA Test Facility to verify the model are also discussed.

1 Introduction

The proposed TESLA 500 linac uses saturated baths of He II (superfluid helium) to maintain the superconducting RF cavities at their operating temperatures. These baths are supplied by a two–phase He II flow. The size of the TESLA 500 is quite large with each refrigerator cooling 2.5 km of linac. Large scale two–phase flow systems have been successfully developed for use in space technology and superconducting magnet stabilization [1]. The principal difference here is the use of He II with its unique heat transfer characteristics and high (compared to He I) ratio of liquid to vapor density.

2 Basics of Modeling

The modeling of a large scale two–phase flow system can be broken down into the following steps :

I : Define the Cooling Scheme and Physical Parameters

Here the basic layout of the cooling system is defined; the operating temperatures and pressures are decided on, the size of the cooling pipes, placement of the J-T valves, the expected heat loads, the various mass flow rates are all specified. The points at which the flow streams combine and separate are located. At this stage, it is also very important to define what physical parameters are most important to the successful operation of the system. These then are the physical and geometrical parameters that should be optimized.

II : Develop a Physical Picture of the Flow

Using experimental and theoretical results estimate what the two–phase flow will look like. Most important is the description of the flow regime (i.e. stratified, wavy, mist, annular). The flow regime determines the hydrodynamics of the problem and the terms in the mathematical model describing the system. Other questions to answer at this stage include whether or not the flow regime will change with changing operating conditions, the importance of heat transfer within the two–phase flow and the role of boiling in the liquid phase.

III : Create a Mathematical Model of the System

From the results of steps I and II a mathematical model of the two–phase flow may be created. Typically, this is done by writing the differential forms of the conservation equations for mass, momentum and energy for each phase along with the initial and boundary conditions for closure. The model will usually simplify the geometry of the system and, in all but the simplest cases, require the use of empirical data. This model may then be numerically solved to make predictions of the system performance.

IV : Consider Unsteady and Transient Conditions

The response of the system to transient effects should be carefully investigated. This effects include both expected operational transients and transients that result from equipment failures. The issue of how best to control the two–phase system should also be investigated.

V : Compare the Model Predictions with Actual Data.

It is clear that assumptions are made throughout this process. These include estimating the flow regime expected and simplifications in the model description. Thus, it is vital that the model predictions are compared to real world data, either from the final system itself or from an experiment that mimics the system under study. As two–phase flow is a complex phenomena, it is ill advised to trust the model results without this sort of test. Based on the comparisons, the physical picture or model may be altered to provide better agreement with the data.

VI : Optimize the System

Once a reliable model exists it may be used to optimize the system to increase reliability and performance. Care should be taken though that changes in the system as part of this optimization do not invalidate the model. Additional experiments may be necessary.

This modeling procedure is shown in Figure 1.

3 Application to the TESLA 500 Cryogenic System

Applying the above procedure to the case of the TESLA 500 two–phase flow system results in the following:

I : System Definition

The TESLA 500 cryogenic system is divided up into 12 units each cooled by a refrigeration plant [2] . The He II two–phase portion of each 2.5 km long unit is divided into 17 strings each with its own J-T valve. Each string contains 96 SCRF cavities divided into 12 cryomodules. Each cavity is contained in a saturated He II bath that is connected to the 74 mm ID two–phase line. Every 12 m (once per cryomodule) the two–phase line is connected to a 300 mm gas return line that takes the helium vapor back to the refrigeration plant. At the end of each string the two–phase line and gas return line are connected to helium bath that contains a level indicator and heater for control purposes. A parallel cooldown / warmup line connects the cavities of each string. A schematic of this system is shown in figures 2 and 3.

The maximum heat load at 2 K into a string is 378 W corresponding to a liquid flow rate of 16.5 g / s. Depending on the operating conditions, the liquid mass flow rate into a string will vary between 1 and 17 g / s.

The most important requirements for the cryogenic system are:

1) A maximum cavity temperature of 2 K. This limits the allowable pressure drop in the two–phase line.

2) A sufficient liquid flow (1 - 17 g / s) to absorb the heat load and keep the cavities covered in He II.

3) A stable system without pressure oscillations that affect the cavity tuning.

In the first 2 units, the linac has a slope of - 5 mrad. This slope results in counter current two–phase flow where the vapor flows uphill and the liquid flows downhill. This is an added complication as the friction between the two phases can limit the mass flow rate of the liquid. These units are not considered in this model. Separate studies of inclined units are underway at the Centre d'Etudes Nucleaires Grenoble [3].

In the original design for the TESLA 500 cooling system analyzed by G. Horlitz [4], the 300 mm line served as the two–phase line without a separate gas return line. This has been changed to reduce the cost of the 300 mm line and thus the cryomodule. An additional benefit of a separate gas return line is that it greatly reduces the vapor flow rate in the two–phase line resulting in a simpler two–phase flow regime.

II : Physical Picture of the Flow

It is expected that the cooling system will begin with the helium vessels full of liquid and a liquid level of approximately 50 % in the two–phase line. Superimposed on this will be a maximum liquid flow rate of 17 g / s. We may think about this situation as a large He II bath over which a small two–phase flow occurs. The supposition is that we will have a well behaved stratified flow.

Alternatively, it may be desirable to operate at much lower liquid levels in the two–phase tube while keeping helium vessels full. As the void fraction in the two–phase line increases, the situation looks less and less like a bath and more like a true two–phase flow system. It's possible that at very large void fractions we may see other flow regimes such as annular or mist flow. However, results from the Centre d'Etudes Nucleaires Grenoble [5] in support of the LHC project imply that our expected superficial vapor velocity (~ 0.5 m / s) is far less than that required for such phenomena.

III : Mathematical Model

Based on the expected physical structure of the flow the following mathematical model may be created : in the case of stratified flow we can use the two velocities, one temperature model. When the void fraction is high (> 0.92) and the superficial gas velocity is also large (approximately greater than 4 m / s) then we have the case of stratified flow with fog (liquid droplets suspended in the vapor) In this case it would be necessary to change the density of the vapor in the model to the density of the fog which is a function of both droplets and vapor.

The two velocity, one temperature model for stratified flow is illustrated in figure 4a. the subscript 1 represents the vapor component and the subscript 2 represents the liquid component. This model makes the following assumptions :

1) The temperatures of the phases are equal to each other and to the local saturation temperature :

$$T_1 = T_2 = T_s (P) \qquad (1)$$

2) All the heat input Q_W goes into evaporating the liquid. Thus the rate of phase conversion I_{21} is given by :

$$I_{21} = Q_W/\zeta \qquad (2)$$

This is a reasonable assumption as the RF heating of the liquid He II is so much greater than the static heat leak. It is this assumption of course that allows us to claim that the temperature of the phases are equal. This assumption will be experimentally verified (see section V).

3) As the two phases are assumed to be in equilibrium the pressure of the phases is equal at any point z:

$$P_1(z) = P_2(z) = P \qquad (3)$$

Using these assumptions we can write the conservation of mass and momentum equations for steady state one–dimensional stratified flow as:

$$\partial\left(\rho_1^0 \, \alpha_1 \, v_1 \right) / \partial z = Q_w/\zeta \; ; \qquad (4a)$$

$$\partial\left(\rho_2^0 \alpha_2 v_2\right)/\partial z = -Q_w/\zeta \, . \tag{4b}$$

$$\partial\left(\rho_1^0 \alpha_1 v_1^2\right)/\partial z = -\alpha_1 \partial P/\partial z + F_{12} - \left(Q_w/\zeta\right) v_{12} - F_{w1}; \tag{4c}$$

$$\partial\left(\rho_2^0 \alpha_2 v_2^2\right)/\partial z = -\alpha_2 \partial P/\partial z - F_{12} + \left(Q_w/\zeta\right) v_{12} - F_{w2}. \tag{4d}$$

Several terms in these equations need further explanation. The wall friction forces (F_{w1} and F_{w2}) may be written in the typical manner as :

$$F_{wi} = \left(\lambda_i \rho_i^0 v_i^2 L_i\right)/2S , \tag{5}$$

where λ_i = the friction coefficient, S = the total cross-sectional flow area = ($\pi D^2 / 4$), and L_i = the perimeter covered by the i-th phase. Similarly, the interfacial friction F_{12} may be written :

$$F_{12} = \left(\lambda_{12} \rho_i^0 v_{12}^2 L_{12}\right)/2S \tag{6}$$

Where $L_{1,2}$ is the chord length of the interface. A further question is what to use for the value of $v_{1,2}$. This is the velocity of the mass undergoing evaporation. Previous work [5] has shown that the vapor velocity in stratified He II two–phase flow is much larger than the liquid velocity. Thus we can start by approximating $v_{1,2} = v_1$.

These equations may be solved using standard numerical techniques to yield $P(z)$, $v_1(Z)$, $v_2(z)$, $\alpha_1(Z)$.

In the more complicated case where we have a stratified flow with a fog of droplets suspended in vapor (figure 4b), the same equations may be used except that the subscript 1 now represents the fog phase and the properties of that phase will be some combination of the vapor and droplet properties. For example:

$$\rho_1^0(fog) = f\left(N, Q_w, v_1, \rho_{liquid}, \rho_{vapor}\right) \tag{7}$$

Where N is the droplet concentration in the fog. The exact form of this functional dependence can only be found from experimental data. Incidentally, the presence of a fog prevents superheating of the vapor ensuring equal phase temperatures.

IV : Transient Conditions

There are two principal issues in the transient response of the TESLA 500 two–phase system. The first is the control of liquid level in the two–phase system. Is this best done by controlling the mass flow rate via the J-T valve, controlling the heater in the reservior at the end of the string or some combination of these approaches ? What level of liquid in the two–phase tube provides optimum control ? The second issue is the response of the system to the sudden removal or addition of RF power. The 2 K heat load changes from 378 W per string to 18 W per string when the RF power is turned off. What is the response of the twophase flow to this change ? Under what conditions will the two–phase tube overfill or dryout ? A simple analysis based on the 74 mm tube being 50 % full says that upon an increase of heat load from 18 W to 378 W the tube will empty in roughly 45 minutes unless the liquid mass flow rate greatly increases. These questions can be investigated with the mathematical model and with experimental results.

V: Compare with Test Data

The TESLA Test Facility (TTF) linac is designed to verify the operation of various TESLA 500 components including the He II two–phase cooling system. This linac currently consists of one cryomodule and will be expanded to 3 cryomodules this year. A schematic of the HE II system of the 3 module linac is shown in figure 5. A further expansion to 8 cryomodules is planned for the year 2002. The maximum 2 K mass flow rate will be 10 g / s by the end of 1998 and roughly 20 g / s by the end of 1999. Thus, once the linac is expanded to 8 cryomodules it will be a good approximation of a TESLA 500 string. In the mean time, tests can be carried out on the 3 module version to check the predictions of the mathematical model. A two–phase flow experiment has been provided by the US National High Magnetic Field Laboratory for installation into the 3 module linac. This test section (described in reference 6) permits measurement of the helium level and the temperature difference between the liquid and vapor components. The helium level measurements will provide some information about the flow regime (stratified, annular, droplet) as well as indicate the presence of flow instabilities. Additional measurements along the two–phase line include total mass flow rate and local pressure (which yields local liquid temperature). A preliminary analysis indicates the necessity of adding an additional helium level measurement at the beginning of the two–phase line. Once the results of the first experiment are known, the test section may be changed be make additional measurements as needed.

While varying the flow rate between 1 and 18 g / s and examining different liquid levels in the two–phase line (e.g. 50 %, 25 %, 10 %, 1%) the following tests can be done:

1) General performance of the two–phase system (pressure drop, temperature distribution, presence of unstable flows)

2) Optimization of helium liquid level control.

3) Response of system to sudden changes in the heat load (e.g. the shut off of RF power)

All these measurements can be compared to model predictions.

4 : Conclusions

A general scheme for modeling the He II two–phase flow has been presented. The expected physical model of the flow for the TESLA 500 system has been described and converted into a mathematical model. The TESLA Tests Facility (TTF) linac has been instrumented so that comparisons between model predictions and experimental data can be made. There is still significant work to be done on this subject :

1) Conversion of the mathematical model into an operating computer code that predicts the behavior of two–phase flow system.
2) Calculation using this computer code of system behavior under expected steady state and transient operating conditions.
3) Taking of experimental data on TTF (both 3 module and 8 module versions).
4) Using the data to refine the model and optimize the final He II two–phase flow system.
5) Separate tests and modeling to address the special case of counter current flow in the inclined section of the linac.

The addition of a separate 76 mm O.D. tube for the two–phase flow and the use of the 300 mm tube as a separate gas return line greatly simplifies the TESLA two–phase flow system in two ways: First, it significantly reduces the vapour flowrate in the two–phase line implying a simpler flow regime (e.g. stratified flow). Second, the change means that the TTF two–phase system is essentially identical to the TESLA 500 one and thus basically full scale tests can be done at TTF. These tests combined with the model will give us much greater confidence in our ability to predict the two–phase flow behavior of TESLA 500.

5 : References

[1] N.N. Filina, J.G. Weisend II, Cryogenic Two-Phase Flow : Applications to Large-Scale Systems, Cambridge University Press, 1996.
[2] R. Brinkmann, G. Materlik, J. Rossbach, A. Wagner, "Conceptual Design of a 500 GeV e^+e^- Linear Cillider with Integrated X - ray Laser Facility ", DESY Report # 1997 - 048, 1997
[3] B. Rousset and A. Gauthier, " Counter Current Flow Study in a 65 mm I.D. Pipe Sized for the TESLA Design ", (at Press)
[4] G.Horlitz "A Study of Pressures, Temperatures and Liquid Levels in a TESLA Subunit", 1995.
[5] B.Rousset, A.Gauthier, L.Grimaud, R. Van Weelderen "Latest Developments on He II Co-current Two–Phase Flow Studies" Adv. Cryo. Engr. 43 (at press)
[6] G. Horlitz, B. Petersen, D. Sellmann, S. W. Van Sciver, J. G. Weisend II, S. Wolff " The TESLA 500 Cryogenic System and He II Two–Phase Flow : Issues and Planned Experiments ", *Cryogenics*, 37: 719 - 725, 1997.

Figure Captions

1 : Procedure for Modeling Large Scale Two–Phase Flow Systems

2: 2 K Cryogenic Supply of a TESLA 500 String

3: Mass Balance for the Two–Phase Pipe in a TESLA String

4 : Possible Two–Phase Flow Regimes for TESLA 500
    a) Stratified Flow
    b) Stratified Flow with Fog

5: Schematic of the Two–Phase Flow System for the 3 Module TTF Linac

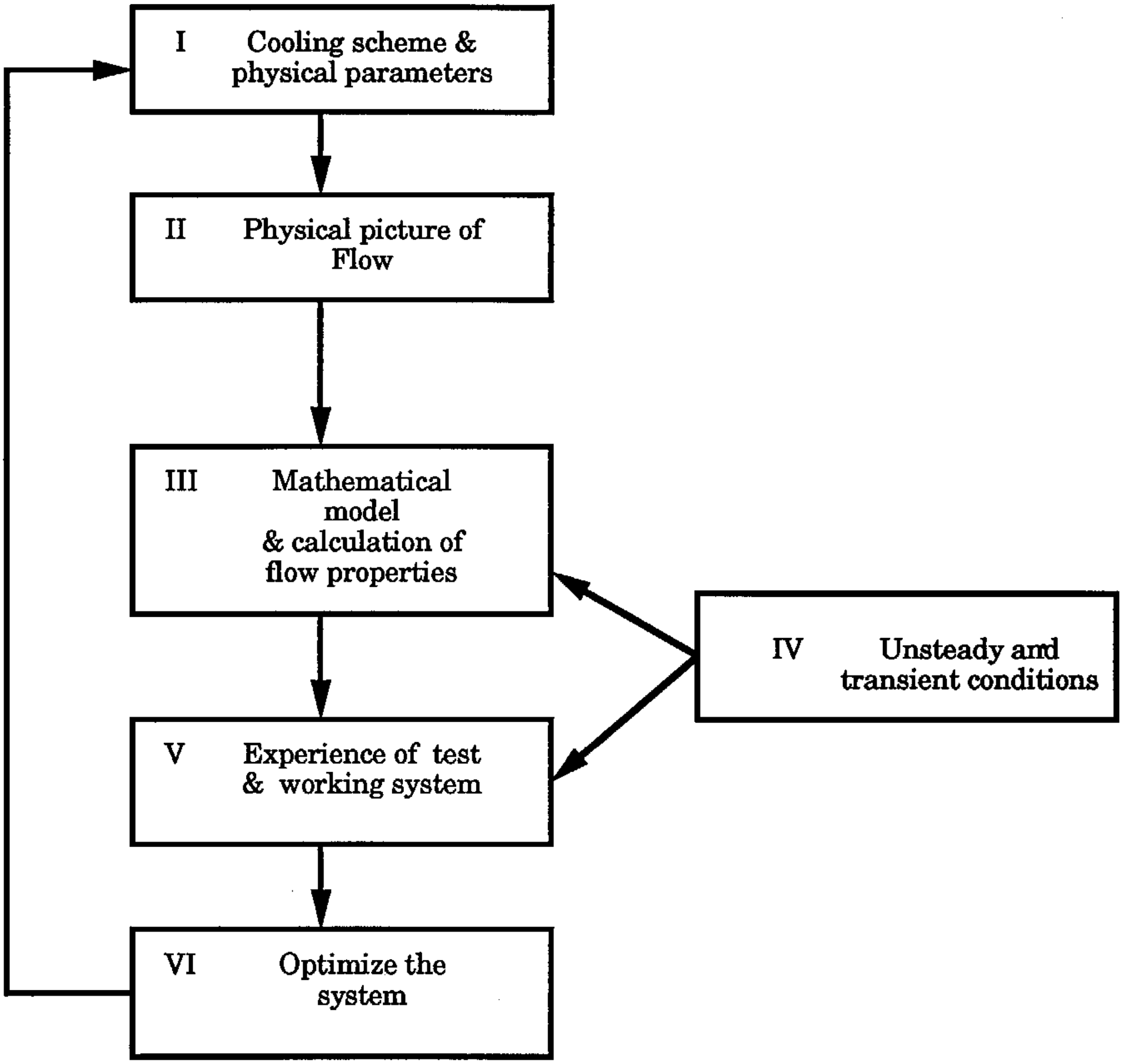
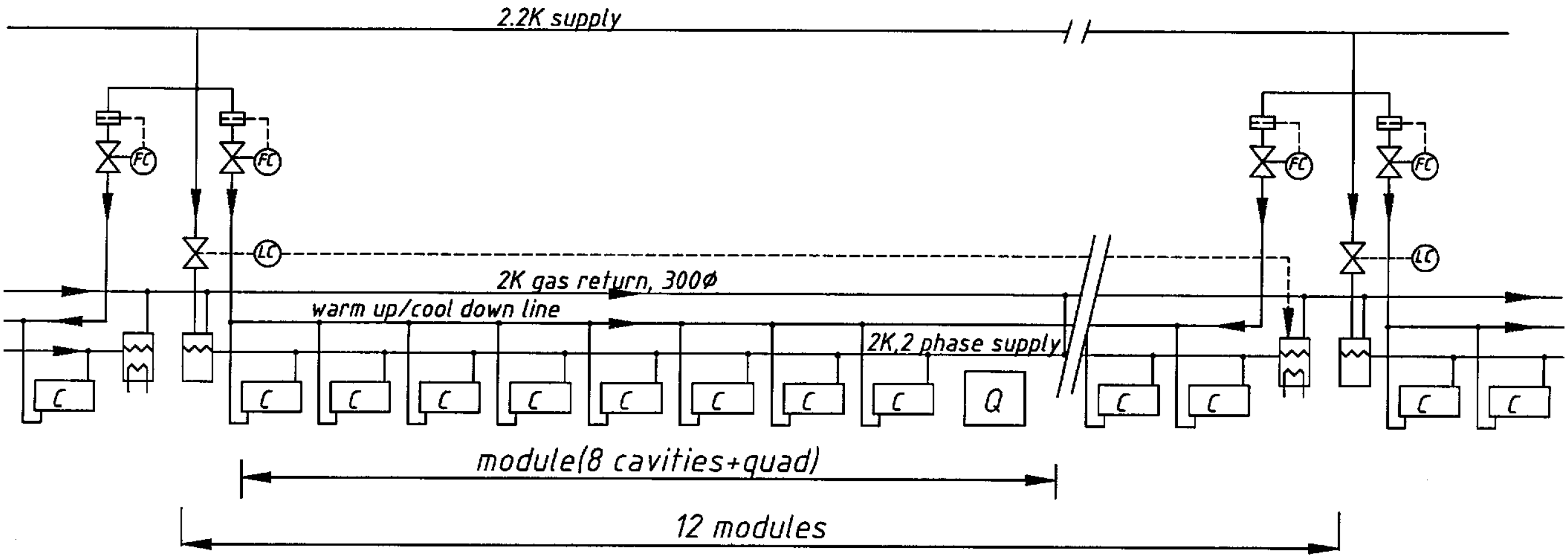

I
Cooling scheme & physical parameters
II
Physical picture of Flow
III
Mathematical model & calculation of flow properties
IV
Unsteady and transient conditions
V
Experience of test & working system
VI
Optimize the system

Fig. 1



Cryogenic Supply of a String.

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Fig.2

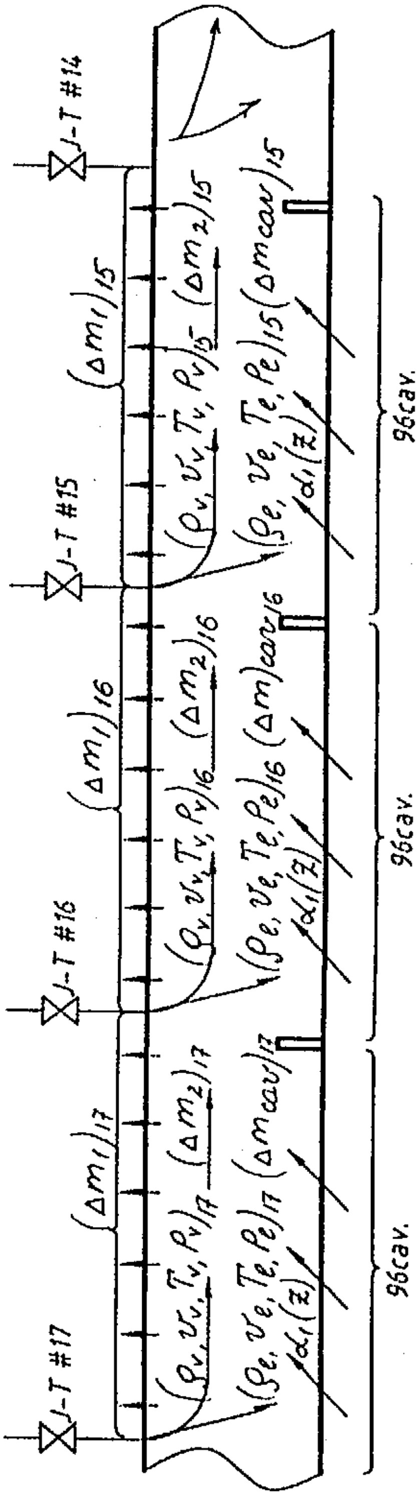
J-T #14
J-T #15
J-T #16
J-T #17
$(\Delta m_1)_{15}$
$(\Delta m_1)_{16}$
$(\Delta m_1)_{17}$
$(\rho_v, v_v, T_v, P_v)_{15}$
$(\rho_v, v_v, T_v, P_v)_{16}$
$(\rho_v, v_v, T_v, P_v)_{17}$
$(\Delta m_2)_{15}$
$(\Delta m_2)_{16}$
$(\Delta m_2)_{17}$
$(\rho_e, v_e, T_e, P_e)_{15}$
$(\rho_e, v_e, T_e, P_e)_{16}$
$(\rho_e, v_e, T_e, P_e)_{17}$
$(\Delta m_{cav})_{15}$
$(\Delta m)_{cav16}$
$(\Delta m_{cav})_{17}$
$\alpha_1(z)$
$\alpha_1(z)$
$\alpha_1(z)$
96cav.
96cav.
96cav.

Fig.3

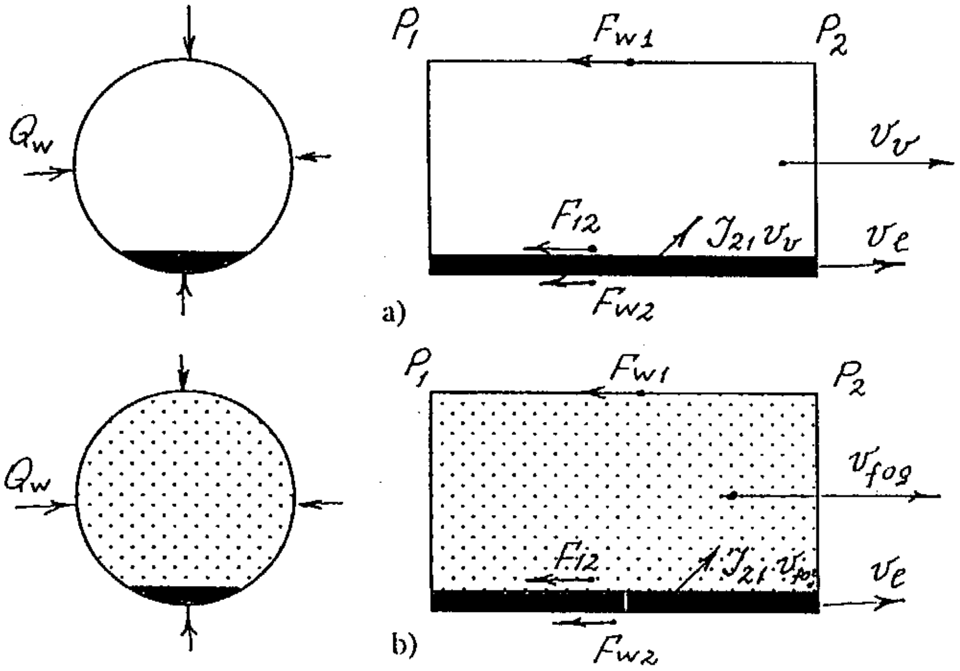
Q_w
P_1
F_{w1}
P_2
v_v
F_{12}
J_{21}, v_v
v_l
F_{w2}
a)
Q_w
P_1
F_{w1}
P_2
v_{fog}
F_{12}
J_{21}, v_{fog}
v_l
F_{w2}
b)

Fig.4

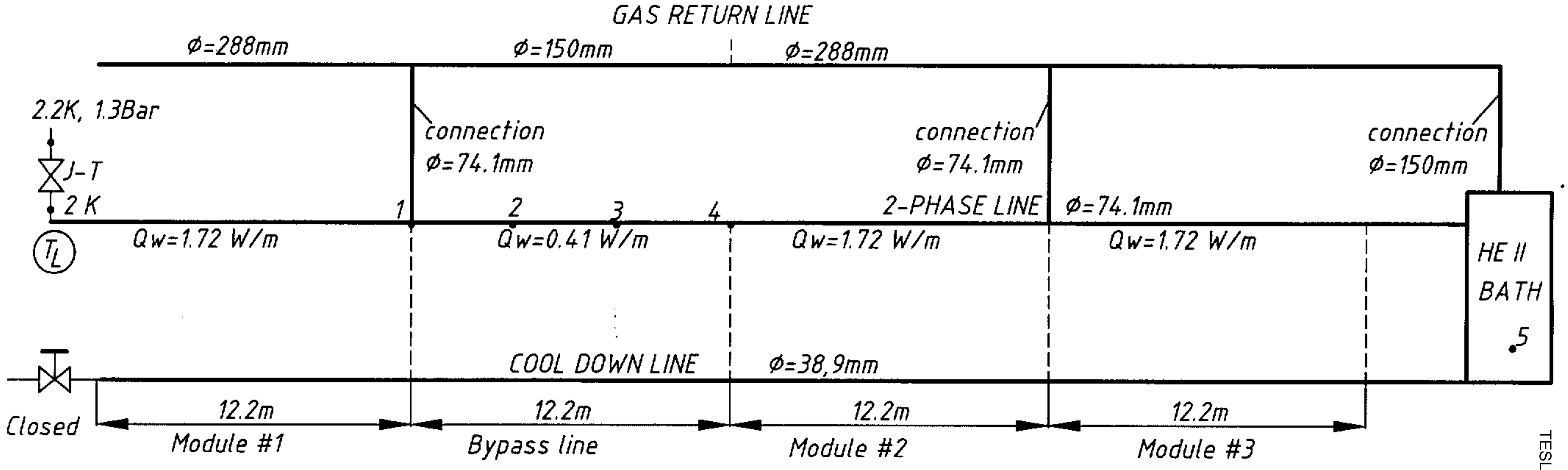
GAS RETURN LINE
Φ=288mm
Φ=150mm
Φ=288mm
2.2K, 1.3Bar
J-T
2 K
T_L
connection
Φ=74.1mm
connection
Φ=74.1mm
connection
Φ=150mm
1
2
3
4
2-PHASE LINE
Φ=74.1mm
Qw=1.72 W/m
Qw=0.41 W/m
Qw=1.72 W/m
Qw=1.72 W/m
HE II
BATH
5
COOL DOWN LINE
Φ=38,9mm
Closed
12.2m
Module #1
12.2m
Bypass line
12.2m
Module #2
12.2m
Module #3

Fig.5