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MHD POWER CONVERSION
EMPLOYING LIQUID METALS

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TH-Report 69-E-06
February 1969

PREFACE

The group Direct Energy Conversion of the Eindhoven University of Technology is aiming at a study of various possibilities of MHD generation of electricity. Therefore, it was considered necessary to study the feasibility of liquid metal MHD systems.
This report contains the results obtained during a study of one year in this topic of research. The results are a bit scattered over the area of investigation because of its large scope. The authors acknowledge stimulating discussions with the colleagues of the group and especially with Prof.Dr. L.H.Th. Rietjens. With regard to the design of a possible test loop, in which high temperature liquid metal experiments can be performed, the authors received extensive support from T.N.O. (Organization for Applied Scientific Research) at Apeldoorn, The Netherlands. Mr. G.L. Polderman and Mr. J. Schapink have aided in the numerical calculations on two-phase flows as a part of their study at the Eindhoven University of Technology.

ABSTRACT

In this report the work is described performed in the field of MHD generation of electricity by means of liquid metals. It is shown that the study of two-phase flows is essential in this topic of research; two-phase flows are described in Section 2. Two types of generators which can be utilised with liquid metals have been studied. The results of this study are described in Section 3. A short survey of the prospects of other liquid metal systems, which emerge from a study of the literature, is given in Section 4. Finally, conclusions are drawn concerning possibilities for further investigation.

CONTENTS

NOMENCLATURE

A	:	cross-sectional flow area
c	:	speed of sound
C_g	:	mass flux of the vapour at the inlet of the channel
C_l	:	mass flux of the liquid at the inlet of the channel
C_{pg}	:	specific heat of vapour per unit mass
C_{pl}	:	specific heat of liquid per unit mass
h_g	:	enthalpy of vapour per unit mass
h_l	:	enthalpy of liquid per unit mass
k	:	constant of Bankoff
p	:	pressure
R	:	gas constant
S	:	entropy per unit mass
s	:	slip ratio
T	:	temperature
T_g	:	vapour temperature
T_l	:	liquid temperature
$\vec{u}$	:	velocity of the centre of mass
$\vec{u}_g$	:	velocity of the vapour
$\vec{u}_l$	:	velocity of the liquid
u_{ref}	:	reference velocity
W	:	molecular weight
x	:	quality
α	:	void fraction
Γ_g	:	rate of vapour mass formation per unit volume
Γ_l	:	rate of liquid mass formation per unit volume
η	:	thermodynamic efficiency
μ	:	ratio of the mass of vapour to the mass of liquid per unit volume of the mixture
ρ	:	mass density of the mixture
ρ_g	:	mass density of the vapour
ρ_l	:	mass density of the liquid
$\bar{\omega}$	:	specific power

1. INTRODUCTION

It is a well-known fact that the generation of electric energy by means of the magnetohydrodynamic (MHD) principle using plasma as a medium, gives many technological problems. The hot plasma must be prevented from getting into contact with the cold walls. As soon as the plasma strikes the wall it will cool and the electrical conductivity will drop sharply. Consequently, the electric power output will decrease. Moreover, there is no material available that can withstand the high plasma temperature.

In order to compete with existing electric energy producing systems, liquid metal MHD loops must operate in a temperature range up to 1000 ^{o}C. In principle, the same conversion efficiency can then be reached as in plasma systems working with a maximum temperature of 2500 ^{o} C. For instance, for a liquid metal MHD steam binary cycle, overall efficiencies of 50 % have been calculated for inlet temperatures of 900 ^{o}C (1). A pure regenerative plasma MHD cycle (2) must approach temperatures of 2200 ^{o}C to achieve an efficiency of 50 %. Liquid metal generators are under construction, although some technological difficulties still have to be solved. Liquid sodium, the coolant of a nuclear reactor, may be used as a medium. In our work we have explored the possibilities of liquid metal MHD systems.

Under ideal circumstances the electric energy output is equal to the decrease of the enthalpy of the liquid metal as this passes through the generator. An important contribution to the energy output results from the decrease of the kinetic energy of the liquid metal. The thermal energy that the medium receives in the heat source is transformed into kinetic energy. This means an additional energy transformation where extra losses occur. The transformation of thermal energy into kinetic energy is realised by using two-phase flows. Evaporation and condensation may, moreover, be important in liquid metal MHD generators. Therefore, work has been done on the description of two-phase flows, the result of which is reported in Section 2.

A detailed study of the possibilities of a direct conversion of the thermal energy of the reactor coolant into electric energy seems to be worthwhile. This direct conversion may be realised in an emulsion-flow generator as described in Section 3.1. The results from our study on this type of generator show that its feasibility is limited. The film-flow generator described in Section 3.2 may offer better prospects.

Part of our work in the field of liquid metals has been to estimate the prospects of other liquid metal MHD systems described in the literature. A survey of our impressions regarding these prospects, including the results published at the Warsaw conference (July 1968), is presented in Section 4.

2. THE DESCRIPTION OF A TWO-PHASE FLOW

As mentioned in the introduction, a detailed knowledge of two-phase flows is necessary before a liquid metal MHD system can be realised. For a complete description of a two-phase flow a continuity, a momentum and an energy equation for both the liquid and the vapour (or gas) component should be available. The main problem is to describe the mass, momentum and energy transport between the two phases. An additional complication is that these transport processes are strongly dependent on the flow configuration. This varies rather drastically from vapour bubbles in liquid (emulsion flow) to liquid droplets in vapour (fog flow) with increasing void fraction. General expressions for the transport terms are not available; expressions valid for specific flow configurations are very scarce. Another complication arises in the description of a two-phase conducting medium. If such a medium passes through a magnetic field, the Lorentz force will influence the two phases in a different way.

The above-mentioned set of equations, required for a complete description, is generally reduced to a less complicated set by making certain assumptions. If we assume that at each point in the channel the temperatures of liquid and vapour are equal, then only the energy equation of the two-phase mixture as a whole will be required. The unknown energy transport between liquid and vapour can then be eliminated from the equations. When introducing a correlation between the liquid and vapour velocity, which can only be realised for a one-dimensional flow problem, only the momentum equation of the mixture as a whole will be necessary. The unknown momentum transport between liquid and vapour does not occur in this equation. Furthermore, it is often assumed that there is no mass transport between the phases, so that the processes of evaporation and condensation are not described. The equations are formulated without the presence of a magnetic field.

2.1 NON-EVAPORATING FLOW

Equations (1) to (13) can be used for describing a homogeneous flow of argon bubbles in liquid sodium, in which the temperatures of gas and liquid are equal. The slip relation of Bankoff is used (3). The following additional assumptions are made: a one-dimensional stationary flow in the direction of the z-axis is analysed and there is no mass exchange between the phases. Gravitation, viscous effects, as well as heat exchange with the surroundings are neglected. The liquid is supposed to be incompressible and the gas is considered an ideal gas. The temperature-range used is chosen so that the saturation pressure of the sodium can be neglected in comparison with the pressure of the argon gas. The resulting equations have been taken from (4) *). The continuity equation for the gas:

$$\frac{d}{dz}\left\{ \alpha \rho_g u_g A \right\} = 0 \qquad (1)$$

The continuity equation for the liquid:

$$\frac{d}{dz}\left\{ (1-\alpha)\rho_l u_l A \right\} = 0 \qquad (2)$$

The momentum equation for the mixture:

$$\frac{d}{dz}\left\{ \rho_l u_l^2 (1-\alpha)\, A + \rho_g u_g^2 \alpha A \right\} = - A \frac{dp}{dz} \qquad (3)$$

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*) It appears from the literature (5) that the formulation of the term $\nabla.(\vec{pu})$ of the energy equation of (4) is not correct. Splitting the term $\nabla.(\vec{pu})$ into contributions of the vapour and the liquid, the velocity of the centre of mass

$$\vec{u} \equiv \frac{\alpha \rho_g \vec{u}_g + (1-\alpha)\rho_l \vec{u}_l}{\rho}$$

must be substituted. This results in the energy equation used.

The slip relation of Bankoff (3):

$$s = \frac{u_g}{u_l} = \frac{1 - \alpha}{k - \alpha} \tag{4}$$

This slip relation has been derived from an averaging procedure over the cross-section of the channel. Averaged gas and liquid velocities can be defined by choosing specific profiles over the cross-section for the local velocities of liquid and gas and for the void fraction; it is assumed that locally no velocity slip occurs. The Bankoff relation defines the ratio of these velocities; k is the constant of Bankoff, which is dependent on the profiles used.
The energy equation for the mixture:

$$\frac{d}{dz}\left\{ \left(\rho_l u_l (1 - \alpha) h_l + \rho_g u_g \alpha h_g \right) A + \frac{p}{\rho} \left(\alpha \rho_g u_g + (1 - \alpha) \rho_l u_l \right) A \right\} = 0 \tag{5}$$

The assumption about equal temperatures:

$$T_g = T_l = T \tag{6}$$

Apart of the prescribed area variation

$$A = A(z) \tag{7}$$

the following equations of state (in which equation (6) is used) are still required:

$$h_l = C_{pl} T + \frac{1}{2} u_l^2 \tag{8}$$

$$h_g = C_{pg} T + \frac{1}{2} u_g^2 \tag{9}$$

$$p = \rho_g \frac{R}{W} T \tag{10}$$

$$\rho_l = f_l(T) \tag{11}$$

$$C_{pl} = f_2(T) \tag{12}$$

$$C_{pg} = f_3(T) \tag{13}$$

Two-phase flow problems, satisfying the model described above, can be solved with this set of 13 equations containing 13 unknowns. Numerical solutions of these equations have been obtained for a weakly diverging channel using an EL-X8 computer. The following conditions at the inlet of the channel have been used: k = 0.92 or 1.00; α = 0.5; T = 700 ^{o}K; u_1 = 50 m/sec; ρ_g = 3.48 kg/m^3.

An important result of the numerical solution is that the temperature T appears to be nearly constant. This may be explained as follows. The maximum void fraction appearing in the calculations is about 0.85, which implies that the flow is a configuration of gas bubbles in a liquid. For this configuration the assumption $T_g = T_l$ may be justified, because there is a good heat contact between the two phases. The mixture has a high heat capacity and acts as a heat reservoir, so that the temperature variations are limited. Using this result, more information can be obtained about the model described by analytical approach. In this analysis it is assumed that the speed of sound also has to be calculated under isothermal conditions, although this cannot be concluded strictly from the above. The speed of sound is then defined by:

$$c = \sqrt{\{\frac{\partial p}{\partial \rho}\}_T} \tag{14}$$

The relation between p and ρ is *)

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*) From integration of equations (1) and (2) it is clear that the quality x defined by

$$x = \frac{\alpha \rho_g u_g A}{\alpha \rho_g u_g A + (1-\alpha)\rho_l u_l A} = \frac{1}{1 + \frac{1-\alpha}{\alpha} \frac{\rho_l}{\rho_g} \frac{1}{s}}$$

is constant. The relation (15) is obtained by using the equations (4), (10) and the usual definition $\rho = \alpha \rho_g + (1-\alpha)\rho_l$.

$$p = \frac{RT}{W}\left(\frac{\rho + (k-1)\rho_1}{k + \frac{1-x}{x}\left(1 - \frac{\rho}{\rho_1}\right)}\right) \tag{15}$$

where in this case k, x, ρ_1 and T are constant.
From equations (14) and (15) the isothermal speed of sound is:

$$c = \frac{1}{\alpha}\sqrt{\frac{RTkx}{W}} \tag{16}$$

It should be noted that the numerical results as illustrated in Figures 1 and 2 show a change of sign of the derivatives for the quantities of interest for certain values of the inlet conditions. This is similar to the influence of the Mach number in a compressible one-phase flow. The analytical approach shows, moreover, that a fictitious Mach number

$$\frac{u_{ref}}{c}$$

may be introduced in our two-phase flow, where

$$u_{ref} = \sqrt{\left\{ x u_g^2 + (1-x)\, u_1^2 \right\}} \tag{17}$$

The derivatives change sign when this Mach number goes through one. The interesting fact is that the two-phase Mach number is defined with the reference velocity (17) which differs from the velocity of the centre of mass

$$\vec{u} \equiv \frac{\alpha\rho_g\vec{u}_g + (1-\alpha)\rho_1\vec{u}_1}{\rho} \tag{18}$$

The restrictions made in another model appearing in the literature have become more explicit as well. In this model (6) the ratio of the mass of the gas to the mass of the liquid

$$\mu = \frac{\alpha\rho_g}{(1-\alpha)\rho_1} \tag{19}$$

is assumed to be constant. Comparison with equation (26b) shows that in this model in fact two assumptions have been made. The quality x is constant and s = 1. The applicability of this model is very limited but its advantage is that it permits analytical solutions. In this model it is also possible to obtain an expression for the isothermal speed of sound:

$$c = \frac{1}{\alpha}\sqrt{\frac{RT}{W}\,\frac{\alpha}{1-\alpha}\,\frac{\rho_g}{\rho_1}} \tag{20}$$

It can easily be verified that (16) yields the same result if there is no slip so that k = 1.

2.2 FLOW WITH EVAPORATION

For a good understanding of the MHD generators described in Section 3, it is necessary to describe the processes evaporation and condensation. A few remarks on this problem are made.

The following continuity equations are now used.
Continuity equation for the vapour:

$$\frac{d}{dz}\left\{\alpha\rho_g u_g A\right\} = \Gamma_g \tag{21}$$

Integration of (21) yields:

$$\alpha\rho_g u_g A = C_g + \int_{z_o}^{z}\Gamma_g dz \tag{22}$$

Continuity equation for the liquid:

$$\frac{d}{dz}\left\{(1-\alpha)\rho_1 u_1 A\right\} = \Gamma_1 \tag{23}$$

Or, after integration:

$$(1-\alpha)\rho_1 u_1 A = C_1 + \int_{z_o}^{z}\Gamma_1 dz \tag{24}$$

In a two-phase flow the mass increase of the vapour per unit volume is equal to the mass decrease of the liquid in the same volume, so that:

$$\Gamma_g = - \Gamma_l \tag{25}$$

The quality x for an evaporating system follows from (22), (24) and (25):

$$x = \frac{\alpha \rho_g u_g A}{\alpha \rho_g u_g A + (1 - \alpha)\rho_l u_l A} = \frac{C_g + \int_o^z \Gamma_g dz}{C_g + C_l} \tag{26a}$$

From the first equality the usual relation

$$x = \frac{1}{1 + \frac{1 - \alpha}{\alpha} \frac{\rho_l}{\rho_g} \frac{1}{s}} \tag{26b}$$

is immediately clear. Equation (26a) again shows that the quality is only constant in systems where neither evaporation nor condensation occurs. As has been mentioned before, the mass transport terms Γ_g and Γ_l occurring in the equations (21) and (23), are difficult to describe in an analytical way. Information about these terms, however, can be obtained experimentally.

Differentiation of equation (26a) with respect to z gives:

$$\Gamma_g = \{ C_g + C_l \} \frac{dx}{dz} \tag{27}$$

When the quality x has been measured as a function of z, a system with mass transport between the vapour and the liquid can be solved numerically, using the equations (21), (23), (25), (27) and (3) to (13). Generally the quality cannot be determined by measuring one quantity only. Assuming thermal equilibrium and using the slip relation of Bankoff, two quantities still have to be measured to determine the quality. It will be clear from (26b) that by measuring the temperature and the void fraction through the channel, the quality as a function of z can be determined. If the quality through the channel is known, Γ_g

can be calculated from (27). Zuber [7] has developed a model in which the measurement of one quantity will suffice for the analysis of a two-phase flow including evaporation. By making rather drastic assumptions, he shows that $\alpha(z)$ can be determined when $T(z)$ has been measured. One of Zuber's problems is to know the exact position $z = z_o$ in the channel where the evaporating process sets in; at this point the void fraction is still equal to zero. The point $z = z_o$ is the starting point of his integrating procedure, on which his mathematical description is based.

3. STUDY ON TWO-PHASE FLOW GENERATORS

In this section the results of a study of two types of MHD generators used with liquid metals are described. The emulsion-flow generator is described in Section 3.1. The limitations of this type of generator, which have emerged from this study, have led to the investigation of the prospects of the film-flow generator. This type of generator is described in Section 3.2.

3.1 THE EMULSION-FLOW GENERATOR

It can be shown that thermal energy cannot be utilised in a direct current MHD generator working with an incompressible medium. It appears that in this type of generator the electric power output results from a decrease of the pressure and of the kinetic energy of the MHD medium. At the same time the temperature of the medium increases as it passes through the generator. So the generator creates an effect opposite to the one intended, namely the conversion of heat into electric power. This type of generator can, therefore, only be used when the thermal energy of the medium is transformed into kinetic energy before the medium enters the MHD channel. Thus, in this process the energy has to be converted in two distinctly separate steps which will be called, after Radebold (8), a two-step process *).

It will now be shown that a one-step process, in which thermal energy is converted directly into electric energy, will be possible if an emulsion-flow generator is used **). The starting point is a loop containing one component, for instance sodium. Both vapour and liquid may occur in the generator. The operation of the generator will be

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*) It should be noted, however, that most two-step processes use an alternating current generator.

**) In the emulsion-flow generator some steps of energy transformation take place in the MHD channel itself. This process is defined as a one-step process.

explained by means of a T-S diagram for sodium, part of which is presented in Figure 3. It is supposed that the medium leaving the heat source, which can be a sodium cooled reactor, may contain a small amount of vapour. Therefore, the medium is compressible, which means that it is not essential to convert its thermal energy into kinetic energy before leading it into the generator. The expansion of the MHD medium will occur in the generator itself. Figure 3 shows that the expansion will be accompanied by further evaporation of the liquid as long as the quality is less than 0.3 and if the expansion is assumed to occur isentropically. It will be shown that this fact will make the one-step process possible. For this, the arguments will be simplified, since the role of the liquid and the vapour will be considered completely separately. As the name suggests, it is essential to realise an emulsion flow in the generator. It has been mentioned in Section 2 that the contact area and hence the heat transfer between vapour and liquid will be large in this case. Moreover, the heat capacity of the liquid is much larger than that of the vapour. This implies that the heat of evaporation and also the heat utilised for the expansion are supplied by the liquid only. In other words, the thermal energy of the liquid phase, which generally cannot be used in one-phase flow generators, is transferred to the vapour phase and then converted into expansion work. However, this work is transferred back to the liquid since the vapour bubbles are completely surrounded by it. In this way the liquid can do work against the Lorentz force induced by the magnetic field and will generate electric power. From this it is clear that some steps of energy transformation take place in the conversion of thermal into electric energy. The difference with the two-step processes, however, is that all these transformation steps occur in the emulsion-flow generator itself. It must be observed that a similar type of generator is being studied by Petrick (9). Since Petrick has scarcely explained the operation of his type of generator it appeared only during our study that both types are in fact identical.

Apart of its greater technical simplicity, a one-step process has the advantage that the velocities, and therefore the losses due to friction with the walls, are smaller than in two-step processes. Another advantage is that the separation of liquid and vapour (or the condensation of the latter), which is essential in two-step processes and which is attended

by large losses, is no longer necessary. Altogether this results in a better internal efficiency of one-step processes in comparison with two-step processes. Radebold (8) estimated that the total efficiency of a one-step process may reach 36 per cent of the thermodynamic efficiency, whereas this number will be only 22.5 per cent in case of a two-step process. Thus, a one-step process, in which the studied emulsion-flow generator may be used, offers important advantages.

As has been mentioned before, it is essential to maintain an emulsion flow in this type of generator. This is of importance in connection with the efficient transfer of the expansion work from the vapour to the liquid. With regard to the electrical conductivity of the two-phase medium it is, however, also necessary to have an emulsion flow. As the amount of vapour in the medium increases, the emulsion flow will ultimately change into a fog flow, which cannot be used in the MHD generator. In the fog flow, which consists of small liquid droplets in vapour, the electrical conductivity is mainly determined by the vapour. Thus, the conductivity is extremely bad, which implies that the electrical efficiency and the electric power output will then be very low. In order to judge the feasibility of this type of generator, it is therefore necessary to know in which range of void fractions the emulsion flow can exist. Petrick (10) states that the maximum allowable void fraction up to which the emulsion flow will be stable is 0.85. This is based on measurements of the electrical conductivity of a two-phase medium in a magnetic field. It appeared from this that the conductivity drops sharply beyond $\alpha = 0.85$ indicating the change in the flow configuration.

Using the fact that the expansion in the generator can only proceed until $\alpha = 0.85$ is reached, the specific power $\bar{\omega}$ and thermodynamic efficiency η of a loop with an emulsion-flow generator can be calculated from Figure 4 and the part of the T-S diagram shown in Figure 3. It is assumed that the expansion occurs isentropically, that the equation of state of the vapour is the ideal gas law and that vapour and liquid will be in thermal equilibrium. In the calculations the change of the liquid density ρ_l with the temperature has been taken into account. The maximum temperature, which will occur at the entrance of the generator, is taken equal to 960 ^{o}C, being the highest value appearing in the complete T-S

diagram. It should be mentioned that this diagram, which has also been used in drawing Figure 4, has been calculated at the Allgemeine Elektrizitäts Gesellschaft (A.E.G.), Berlin (11). Two cases will be distinguished for the calculations.

(i) At the entrance of the generator the state of the medium is given by the point on the liquid line x = 0. It is assumed, after Petrick (12), that the average slip in the channel will be constant, namely s = 2.

Using equation (15) the point on the isentrope going through x = 0, T = 960 °C, where $\alpha = 0.85$ is reached, can be found. In the calculation an iteration is necessary in the value of T in order to find this point. The result is that the generator can only operate in the range

$$945\ ^{o}C \leq T \leq 960\ ^{o}C$$
$$1.75\ \text{bar} \leq p \leq 1.97\ \text{bar}$$

The loop, which is described in the T-S diagram, therefore encloses a very small area; it is shown separately in Figure 5a (note the difference in scale with respect to Figure 3). The enclosed area in the T-S diagram is a measure of the specific power and the thermodynamic efficiency. These are therefore very low, viz.

$$\bar{\omega} = 0.12\ \frac{\text{kW}}{\text{kg/sec}}$$
$$\eta = 0.61\ \%$$

(ii) According to Petrick (9) it is also possible to operate an emulsion-flow generator at α = constant. The increase in void fraction, which would occur owing to the pressure decrease, is then compensated by an increase in relative velocity between the two phases. The calculation is therefore performed for $\alpha = 0.85$ while the slip increases from s = 1 at the entrance to s = 3 at the exit of the generator. The result is that the generator can then operate in the range

$$946\ ^{o}C \leq T \leq 960\ ^{o}C$$
$$1.77\ \text{bar} \leq p \leq 1.97\ \text{bar}$$

The loop described in the T-S diagram appears separately in Figure 5b. The enclosed area in this diagram is now slightly larger, so that specific power and thermodynamic efficiency will also be somewhat higher than in case (i). The values of $\bar{\omega}$ and η are, however, still unfavourable, namely

$$\bar{\omega} = 0.28\ \frac{kW}{kg/sec}$$
$$\eta = 0.82\ \%$$

The disappointing conclusion from the calculations above is that the specific power and the efficiency of the loop studied are too low to be of interest in practice. After this conclusion was reached, it appeared that Petrick (13) considered coupling a series of loops to each other to obtain better values of $\bar{\omega}$ and η. This possibility, however, was considered not to be promising to such a degree as to justify investigation of its prospects any further in our group.

It should be mentioned that the feasibility of the emulsion-flow generator is more favourable if two different components are used. The reason for this is that the value of the quality corresponding with $\alpha = 0.85$ is mainly determined by the density ratio ρ_g/ρ_f. In a one-component system, which has been studied above, this ratio is fixed when the temperature has been chosen. In a two-component system one component will be present as a vapour whereas the other will remain in the liquid state. The components can then be chosen so that a more favourable density ratio is obtained, which implies that the expansion in the generator can proceed over a larger temperature range. The operation of this type of emulsion-flow generator will be somewhat different from the description above. Evaporation of the liquid in the generator is no longer essential; quite often this has even to be considered as a loss factor and has then to be restricted.

The feasibility of a two-component system can be determined in a way similar to the above. For this, a T-S diagram for the chosen two-

component, two-phase mixture has to be constructed. Moreover, another choice has to be made, namely the mixing ratio of the two components, since this will influence the shape of the constant quality lines in this diagram. It will be clear from what has been said above that the form of these lines affects the temperature range over which expansion is possible. According to Bidard and Sterlini (14) this temperature range will, however, still be limited to such an extent that several mutually coupled loops are necessary when an emulsion-flow generator working with two components is used. Since a single loop with an emulsion-flow generator apparently always encloses a small area in the T-S diagram, it was decided to study a totally different type of generator, which is less restricted in this respect. This type of generator studied is the film-flow generator, which will be discussed now.

3.2 THE FILM-FLOW GENERATOR

The advantages resulting from increasing the enclosed area in the T-S diagram, will be very important as can be seen from Figure 6. This figure is valid for a single loop with one component, namely sodium (just as in Section 3.1), when the expansion is isentropic and when the maximum and minimum temperatures are fixed. In order to benefit from the advantages shown in Figure 6 the film-flow generator works at a much higher vapour quality than the emulsion-flow generator. In that case a fog flow will occur, which has very low electrical conductivity. Therefore, the generator is constructed so that a liquid film (with a much higher conductivity than the main flow) will be built up on the wall to which process condensation on the wall may add. This type of generator has also been proposed by Petrick (9), who arrived at this concept from conclusions similar to those mentioned at the end of the previous section. As will be clear from the above, only the liquid film can generate electric energy. Since the film is incompressible and since it can only withstand a limited pressure difference, an important contribution to the electric energy has to result from a decrease of its kinetic energy. Therefore, the liquid film must have a high velocity, which implies first of all that the fog flow has to be accelerated in a nozzle before it is led into the

generator. The film-flow generator can thus only be used in a two-step process. The disadvantages of a two-step process mentioned in the previous section will have to be put up with. It appears possible, however, to diminish the effect of one of these disadvantages. The friction losses on the walls, which are in general larger in two-step processes than in one-step processes, may, in fact, be reduced by injecting liquid through the walls.

Another problem in the operation of this type of generator is an efficient transfer of kinetic energy from the fog flow to the liquid film. It appears possible to promote this energy transfer and the building up of the liquid film by creating stable vortices in the flow. In Petrick's concept the liquid film is built up in a rather crude way; the flow simply impinges under a small angle upon the lower wall of the generator. Another improvement may be to give a certain curvature to the upper wall of the generator, which in Petrick's scheme is flat, so that centrifugal forces will also aid in building up the film.

An advantage of a loop with a film-flow generator is again its technical simplicity. Notably the separation of liquid and vapour, which has to take place in front of the generator in many of the two-step processes, here occurs in the generator itself. It is practically impossible to estimate the generator efficiency of a film-flow generator, because the required experimental information is not available. This implies that the feasibility of the loop studied can only be judged when this efficiency has been determined experimentally. This is especially important in connection with a remark made by Péricart (15), namely that the operation of the generator will depend on the quality. If the quality before the expansion is chosen too high, enough condensation will not occur, which implies that the liquid film will not be built up properly. The consequence of this is that there may occur a maximum in the net specific power and in the total efficiency of the loop at a certain value of the quality. It is thus not realistic to judge the

loop studied only on the basis of Figure 6 *).

From the foregoing the conclusion can be drawn that the efficient separation of liquid and vapour without large losses in kinetic energy is a major problem in the film-flow generator. It should be noted that separation (or complete condensation) of vapour and liquid is also an essential point in other two-step processes so that much can be learned from the experience of others. With respect to this, much experience has already been obtained with the separator used at the Jet Propulsion Laboratory (J.P.L.) (16) but it is difficult to see how this can be utilised for the film-flow generator. The creation of stable vortices, which has been proposed above to promote the transfer of kinetic energy from the fog flow to the liquid film, is also essential to the operation of the hollow core jet condenser (17). This apparatus aims at complete condensation of the vapour; the application of vortices is therefore similar to that proposed above, but cannot be utilised in the form studied for a film-flow generator. Finally it should be mentioned that Petrick, who proposed the film-flow generator at the symposium at Salzburg, did not report further progress on it at the symposium recently held at Warsaw.

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*) It should be noted that the relation between $\bar{\omega}$ and x_1 shown in Figure 6 differs from that in Figure 10 of Péricart, which is valid for the same loop. The difference is that Péricart applied an approximation in constructing his Figure 10, whereas Figure 6 has been calculated exactly by means of the T-S diagram that Péricart gives.

4. A SHORT SURVEY ON THE PROSPECTS OF OTHER LIQUID METAL MHD SYSTEMS

A part of our work in the field of liquid metal MHD has been to estimate the prospects of other liquid metal systems appearing in the literature. A short survey will be given in this section of our impressions in this respect. New developments in the different areas, which have been reported at the Warsaw symposium will also be included in this outline.

1. The two-step processes that use one component and fog flow, have been investigated at many institutes (8, 15). It appeared at Warsaw that the prospects of these systems are much worse than had been anticipated. The reasons for this are mainly the large differences in temperature and velocity during the mixing of vapour and liquid in order to accelerate the latter and the very low efficiency of the injection-condensation step (8). A new approach is being studied by the group at A.E.G., which offers better prospects. In this approach a new method of acceleration of the liquid, the fully-carnotised process, and a more refined way of condensing, the hollow core jet condenser, are investigated (17). These new processes have to be investigated further experimentally in order to verify whether higher efficiencies can be obtained in this way.
2. The two-step process that uses two components and fog flow, has been studied for some years in a practically unaltered form at J.P.L. (16). The advantage of this system is mainly that the above-mentioned problem in the acceleration of the liquid, which has led to the fully-carnotised process, can be avoided. The two components, which will ultimately be used at J.P.L., can, in fact, be mixed with hardly any differences in temperature and velocity (16). This system appears to offer the best prospects and is very close to technical realisation.
3. In the one-step process that uses an emulsion flow, Petrick obviously switched over from one to two components. This corresponds with the conclusion reached in Section 3.1. Bidard and Sterlini have also investigated a two-component system. The main difference is that the starting point of Bidard and Sterlini has from the beginning been a series of mutually coupled loops (14), whereas Petrick apparently is of the opinion that a single loop will suffice (13). None of these

systems seem to have come much closer to realisation. The two groups mentioned have mainly performed fundamental studies on two-phase flows (12, 18).

4. At the Warsaw symposium systems have been proposed that use a plug flow or striated flow, the application of which in the field of liquid metals is entirely new. In this flow configuration the vapour bubbles completely fill the channel cross-section; they are mutually separated by liquid metal plugs. The main problems in using a plug flow seem to be instabilities which tend to destroy this flow configuration and the formation of this type of flow. So far the new systems have been studied mainly theoretically. Until the moment that some experimental results have been obtained with these systems, it will be difficult to say much about their prospects.

5. CONCLUSIONS

Within the study reported upon above the following conclusions can be drawn concerning possibilities of further investigation.

1. It appeared from the discussion in Section 2 that more fundamental knowledge is needed in the area of two-phase flows. This extensive area has to be investigated thoroughly; theory and experiment will have to support each other.
2. It will be necessary to investigate the new proposals of the group at A.E.G. further, in order to be able to appreciate the gain that can be obtained in this way. This has to be done also experimentally, since the application of stable vortices will not only be important to the hollow core jet condenser but also to the film-flow generator.
3. It will be necessary to construct T-S diagrams for those combinations of components which will be of interest to an emulsion-flow generator. The prospects of the corresponding systems then have to be analysed in the way described in Section 3.1.
4. Further study is needed of the recently proposed systems using a plug flow.

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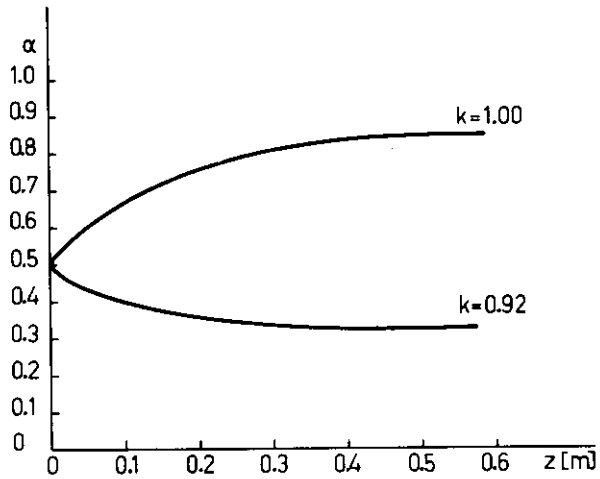

Fig. 1. Void fraction α as a function of the channel distance z calculated from the equations (1) to (13). Solutions are given for two inlet conditions of the constant of Bankoff, k. The other initial conditions are: $\alpha = 0.5$, $T = 700\ ^{o}K$, $u_1 = 50$ m/sec and $\rho_g = 3.48$ kg/m^3.

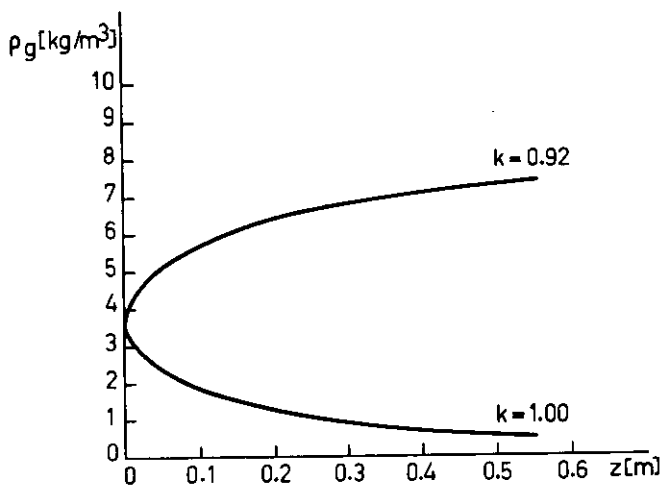

Fig. 2. Mass density of the vapour ρ_g as a function of the channel distance z calculated from the equations (1) to (13). Solutions are given for two inlet conditions of the constant of Bankoff, k. The other initial conditions are: $\alpha = 0.5$, $T = 700\ ^{o}K$, $u_1 = 50$ m/sec and $\rho_g = 3.48$ kg/m^3.

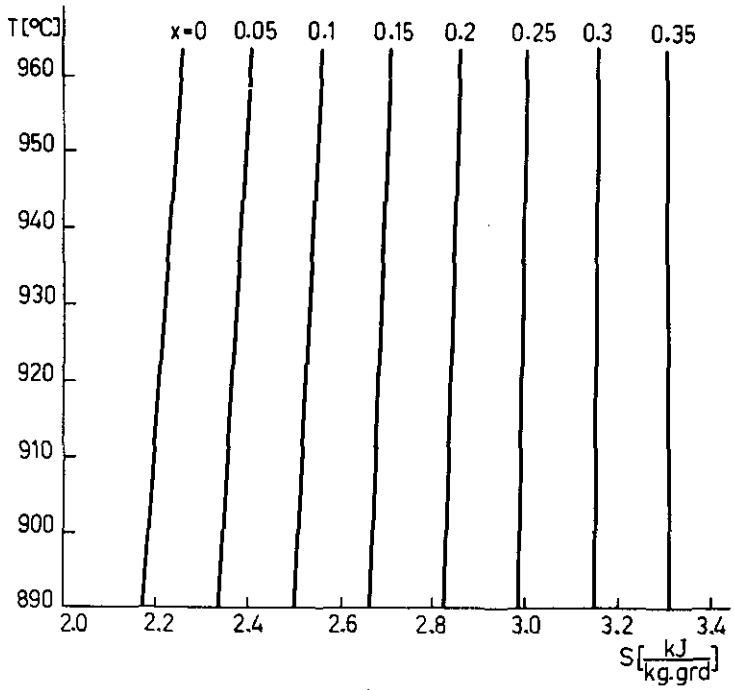

Fig. 3. A part of the T-S diagram for sodium (11).

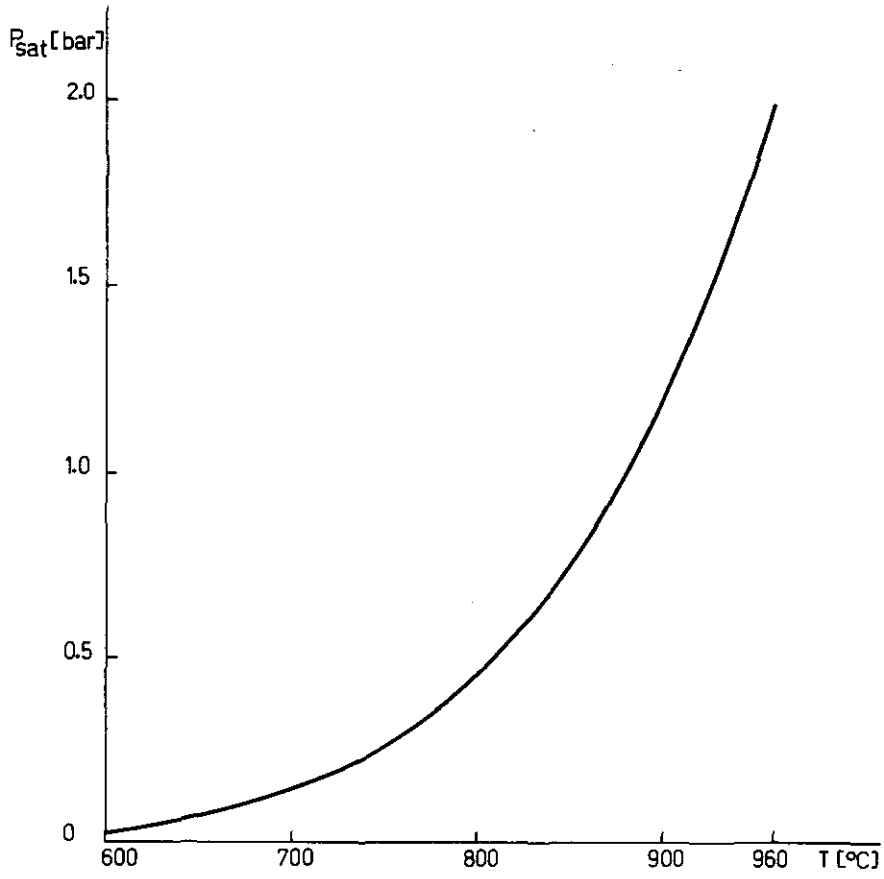

Fig. 4. The saturation pressure P_{sat} as a function of the temperature T for sodium.

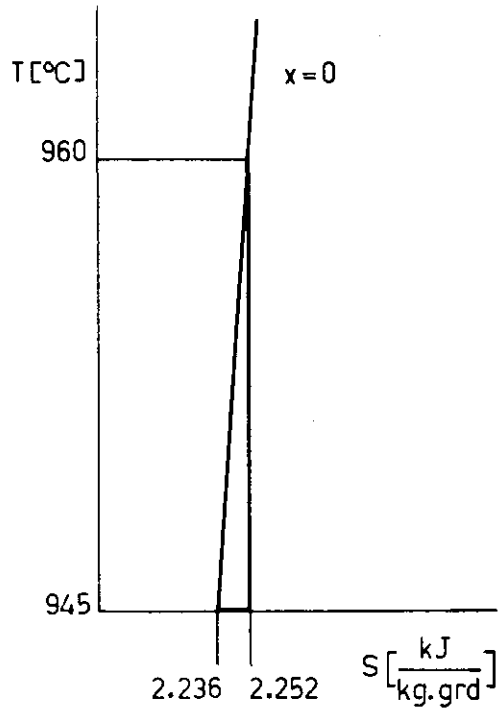

Fig. 5a. The loop in the T-S diagram for an emulsion-flow generator at constant slip ratio s.

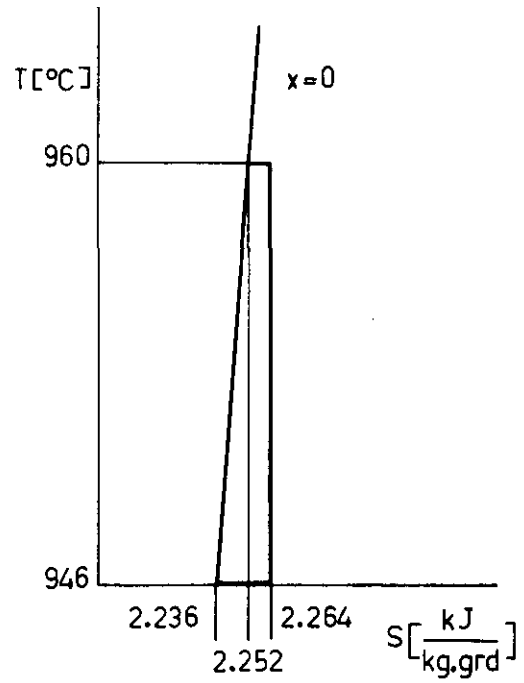

Fig. 5b. The loop in the T-S diagram for an emulsion-flow generator at constant void fraction α.

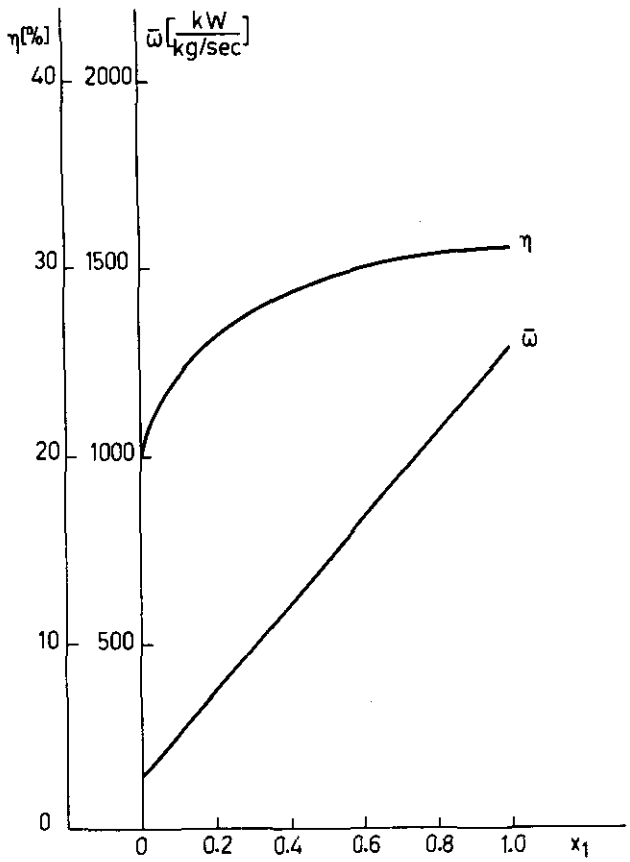

Fig. 6. Variation of the thermodynamic efficiency η and the specific power $\bar{\omega}$ with the quality before the expansion x_1 for single-loop systems working with sodium between 1000 and 1500 ^{o}K.