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Аннотация

В работе рассмотрены математические аспекты задачи растекания расплавленного топлива по бетонному основанию. В качестве основных процессов учитываются процессы тепломассопереноса в растекающемся топливе под действием гравитационных сил в различных приближениях. Полные модели строятся на основе уравнений Навье-Стокса для несжимаемой жидкости, упрощенные модели базируются на квази- двумерном приближении тонкого слоя. В моделях учтены процессы затвердевания растекающегося топлива. Представлены результаты численных расчетов.

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Abstract

In this paper the mathematical aspects of the problem of spreading of molten core onto concrete basemat are considering. As principal processes the heat- and mass transfer in the gravity driven molten corium in different approximations are considering. Full models are based on the set of Navier-Stokes equations for incompressible fluid, simplified quasi two dimensional models are based on the thin layer approximation. The process of corium solidification is taken into account. Computational results are presented.

Modeling of core spreading processes

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Abstract

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1 INTRODUCTION

Ex-vessel behavior of molten core is of great interest for risk assessments of NPP Existing understanding of this behavior includes molten core concrete interaction (MCCI) which was investigated on the base of several large scale experiment series (BETA, ACE) for different scenarios of interaction. Second problem connected with ex-vessel behavior is core spreading. This problem is of great importance for some containment designs and very important as one of the conceptual approaches to core catcher problem. It is well known now that core spreading played very important role for Chernobyl accident and prevented intensive core concrete interaction [1].

Understanding of the importance of core spreading phenomena leads to the development of codes (for instance MELTSPREAD [2]) and to proposals to carry out special programs for experimental investigation of related phenomena [3].

In this paper models developed for modeling of core spreading investigations are described. These models are realized as the part of computer code RASPLAV/SPREAD [4] for modeling of thermal hydraulic phenomena in course of severe accidents.

2 PROBLEM OF LONG-TERM KEEPING OF MOLTEN CORE

The problem of designing of passive core catcher and it's preliminary simulation is especially actual for advanced light water reactors (ALWR).

In general two possible scenarios of LHF can be considered: global failure with quick relocation of mixtures into emergency vessel, or into reactor shaft and local melting through reactor walls, or failure of penetrations and relatively small flow rates and spreading.

Depend on scenario of vessel low head failure the following problems are actual:

— corium retaining in emergency vessel;

— corium spreading;

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— molten core-concrete interaction;

— long-term keeping of corium in passive catcher

In the case of the first scenario (complete relocation of active zone) the problem of molten corium retaining in emergency vessel becomes actual. The presence of sacrificial concrete in emergency vessel, which can significantly decreases the temperature of solidification of molten core/ concrete mixture, will lead to absence of crust (solidified core). This peculiarity of molten mixture may be essential during possible cooling of melt both by water at the upper boundary and by air flooding the outer side of vessel.

In case of the second scenario, when the melttrough is possible in some local point of the vessel, it is quite probable that the fuel may flow as directed stream during a long period of time (tens or hundreds seconds). This time is enough for meltthrough of emergency vessel also in some local region. In this connection the following aspects can be outlined:

— Interaction of molten corium jet with the basemat;

— Core spreading onto concrete basemat and core - concrete interaction.

Depend on characteristics of flow and peculiarities of core catcher design, it should be considered some features of core - concrete interaction, namely, possible localization of corium (in the places where partitions are located) with further penetration (as a whole large fragment) into concrete on considerable depth.

In case of the molten core penetration into the passive core catcher it is necessary to highlight the following important problems:

— Long-term keeping of molten core on ceramics/concrete basemat. The main question, which appears in this connection is the maximum depth of molten layer for which water cooling is provide the temperature not higher then melting temperature of ceramics or solidification temperature of corium.

— Since ceramics and have very low thermal conductivity and high melting temperature, it may be expected formation of liquid layer on the boundary of interaction with water Problem of heat exchange on the upper boundary (possible including natural convection).

— In case of "slow" regimes of flow provided by existence of water (at initial time moment or some time later) it is reasonable to suggest, that "tongue" of the molten core lave with the rather thick crust is formed. And this crust will block the melt from water cooling. Inside lave the high temperature may be expected and as a consequence may be circulation in result of natural convection.

Thus, a set of problems may be formulated, which are the most actual during solving of the problem of fuel keeping inside passive core catcher:

— Long-term keeping of corium layer on the concrete basemat in the catcher with water In this case it is necessary to take into account various heat transfer phenomena such as: thermal conductivity with phase transition, natural convection, crust formation, vaporization and recondensation,

— gravity driven flow of molten corium with self-consistent consideration of heat transfer in corium and concrete;

— core concrete interaction including the interaction of solid corium with preheated concrete including case of corium characterized by low value of volumetric heat generation;

— keeping of molten core inside emergency vessel in condition of outer cooling.

3 MAIN PROCESSES

3.1 HEAT AND MASS TRANSFER IN SPREADING MELT

To model heat- and mass transfer processes in spreading melt the following approaches are used:

— interrelated solution of heat transfer and Navier-Stokes equations for incompressible fluid with free boundaries in two dimensional axisymmetrical geometry;

— interrelated solution of heat transfer equation and system of equations of incompressible fluid flow in the thin layer approximation.

These two approaches are differ by models of molten corium flow and by models of heat transfer Heat transfer models include description both the processes in molten corium and processes in basemat materials (concrete, metal or ceramics).

3.2 MCCI PROCESSES

For accurate description of processes taking place during the melt spreading onto concrete basemat, the following models developed for MCCI investigations are used:

— melt attack to the concrete and concrete decomposition;

— sparging of concrete decomposition gases through the molten corium;

— chemical reactions of metal oxidation leading to energy release;

— material properties, such as: solidus temperature, liquidus temperature, viscosity and etc.,

— the interaction of corium with the water including film or nucleate boiling;

— the crust formation and its influence on heat exchange with surroundings.

4 MODELS OF FLOW

In this section the models of gravity driven molten corium is considered. As principal processes the heat- and mass transfer in molten corium are considered. The process of corium solidification is taken into account.

The peculiarity of such type of flow is the presence of free boundaries. Position of such boundaries is unknown, changing during the time and can be defined in process of modeling. This obstacle practically do not allow to investigate full heat and mass transfer system of equations on micro- and minicomputers. Therefore, a great attention is given to designing more simple models of core spreading.

Relatively full models are built on the basis of Navier-Stokes equations for incompressible non-newtonian liquids. More simple models are designed in approximation of thin layer (film flow) and approximation of high viscous (creeping flow) liquids. The simplest mathematical models are based on the some average descriptions of field velocity and lead to the so called "shallow water" approximation.

It should be mentioned two stages of flow during core spreading onto the concrete basemat. The first stage is the forming of spreading flow and the second one is the transformation to film flow The first stage is characterized by small difference of velocities in vertical and horizontal directions. At the second stage when film structure of flow is formed the difference of velocities the scale and linear sizes are significant. It is naturally to develop the mathematical models taking into account such peculiarities of the flow

4.1 GOVERNING EQUATIONS

4.1.1 FLOW OF VISCOUS NON-NEWTONIAN LIQUIDS WITH FREE BOUNDARIES. BASE MODEL

The schematic diagram of the flow considered is shown in fig. 1 Let us define the domain occupied by the molten corium as Ω. Domain geometry may be changed during the time, i.e. $\Omega = \Omega(t)$.

The molten corium is treated as a liquid with complex reologilal properties (non-newtonian liquid) [5]. For heat- and mass transfer description a model of viscous heat conducting liquid is used. Continuity equation is given by [6, 7]:

$$\frac{\partial \rho}{\partial t} + div(\rho \mathbf{v}) = 0, \quad (1)$$

where:

ρ is density,

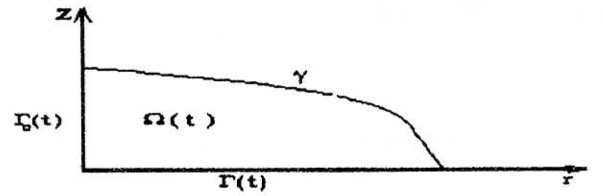

Figure 1: Schematic diagram of flow

v is velocity vector

Momentum equation can be written in form

$$\rho\frac{d\mathbf{v}}{dt} = \rho\mathbf{F} - gradp + div\tau, \tag{2}$$

where:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + (\mathbf{v}grad)$$

is substantial derivative , p is pressure, a τ is tensor of viscous stresses.

The external volume forces (vector **F**) are of the gravitational nature and in our case is written as $F = (0, 0, -g)$, where g is the gravitational acceleration. We shell use the following representation for τ

$$\begin{aligned} \tau_{ij} &= 2\mu D_{ij}, i \neq j, \\ \tau_{ii} &= (\xi - \frac{2}{3}\mu)divv + 2\mu D_{ii}, \end{aligned} \tag{3}$$

where:

μ is dynamic viscosity coefficient,

ξ is second viscosity,

D is velocity- strain tensor:

$$D_{ij} = \frac{1}{2}\Big(\frac{\partial v^i}{\partial x^j} + \frac{\partial v^j}{\partial x^i}\Big), \tag{4}$$

where $x = (x^1, x^2, x^3)$ are Cartesian coordinates.

Energy equation is written in the following form:

$$c\rho\frac{dT}{dt} = div(kgradT) + \Phi, \tag{5}$$

where:

c is specific heat capacity under constant pressure,

T is temperature,

k is thermal conductivity coefficient.

The last term in (5) describes heat release due to the viscous friction. In frames of well known macro models of radiation [8] the approach of radiative losses description is analogous. For dissipative function Φ the following expression is valid:

$$\Phi = div(\tau v) - vdiv\tau \tag{6}$$

Set of equations (1 - 6) is the basic one for the designing more simple models.

4.2 ICOMPRESSIBLE FLOW

The first essential simplification of model (1 - 6) is achieved by using of the approximation of incompressibility. This approximation is suitable for low Mach numbers [7] and can be used in the core spreading modeling.

In this case ($\rho = \text{const}$) continuity equation (1) is transformed to

$$div v = 0. \tag{7}$$

For components of viscous stress tensor we obtain from (4)

$$\tau_{ij} = 2\mu D_{ij} \tag{8}$$

Dissipative function is written in tensor form as

$$\Phi = \frac{1}{2}\mu\Big(\frac{\partial v^i}{\partial x^j} + \frac{\partial v^j}{\partial x^i} - \frac{2}{3}\delta_{ij}\frac{\partial v^k}{\partial x^k}\Big)^2 + \xi(div v)^2, \tag{9}$$

where:

δ_{ij} is Kronecker's delta, in incompressible conditions is simplified as follows:

$$\Phi = \frac{1}{2}\mu\Big(\frac{\partial v^i}{\partial x^j} + \frac{\partial v^j}{\partial x^i}\Big)^2 \tag{10}$$

In expression (10) and here in after the rule of summering for twice repeating indexes is used.

4.2.1 SET OF EQUATIONS IN AXISYMMETRICAL GEOMETRY

Two dimensional heat transfer equation in axisymmetrical geometry is given by:

$$\rho c(T)\Big(\frac{\partial T}{\partial t} + \frac{\partial vT}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(ruT)\Big) = \frac{1}{r}\frac{\partial}{\partial r}\Big(r\kappa(T)\frac{\partial T}{\partial r}\Big) + \frac{\partial}{\partial z}\Big(\kappa(T)\frac{\partial T}{\partial z}\Big) + q, \tag{11}$$

where:

t	—	the time,
(r, z)	—	cylindrical coordinates,
T	—	temperature,
ρ	—	density,
$c(T)$	—	specific heat capacity,
$\kappa(T)$	—	thermal conductivity,
$\dot{q}$	—	volumetric heat generation,
u and v	—	appropriate components of velocity.

Momentum equations can be written in the following form:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial z} = F_r - \frac{\partial p}{\partial r} + \frac{\partial}{\partial r}(2\nu\frac{\partial u}{\partial r}) + \frac{\partial}{\partial z}\Big(\nu(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r})\Big) + \frac{1}{r}(2\nu\frac{\partial u}{\partial r}), \tag{12}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial v}{\partial z} = F_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial z}(2\nu\frac{\partial v}{\partial z}) + \frac{\partial}{\partial r}\Big(\nu(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r})\Big) + \frac{1}{r}\Big(\nu(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r})\Big) \tag{13}$$

Continuity equation under assumption of incompressibility is written as:

$$\frac{\partial(ru)}{\partial r} + \frac{\partial(rv)}{\partial z} = 0. \tag{14}$$

here:

ν	—	kinematic viscosity,
F_r, F_z	—	components of external forces (in this case $F_r = 0$, $F_z = g$),
g	—	free fall acceleration,
β	—	volumetric expansion coefficient,
p	—	pressure.

During initial stage of melt spreading when the flow is essentially unsteady the melt temperature much greater then temperature of solidification and the viscosity can be considered as a constant what simplified solving of heat and mass transfer system of equations.

System (11 - 14) is supplemented by appropriate boundary and initial conditions.

4.2.2 CREEPING FLOW

The second general simplification which may be used for modeling of core spreading is based on the approximation of high viscous(creeping) flows. This approach is suitable, if inertia forces are much less than friction ones , i.e. for low Reynolds numbers ($Re = \rho v_0 h/\mu << 1$, where v_0 is velocity scale, h - reference geometry dimension). For simulation of the core catcher, this approximation is valid because the temperature of the spreading melt is close to the temperature of solidification T_{sol}

So, omitting the left hand of (2), we obtain

$$\rho F - \boldsymbol{gradp} + \boldsymbol{div}\tau = 0. \tag{15}$$

Using (8) let us rewrite (15) as

$$0 = \rho F - \boldsymbol{gradp} + \boldsymbol{div}(2\mu D), \tag{16}$$

where components of velocity strain tensor D is defined by (4).

Thus the models of core spreading is characterized by the suggestion of incompressible liquid and very viscous flow

Let us write governing equations in common coordinate form. From (7) we have

$$\frac{\partial v^i}{\partial x^i} = 0. \tag{17}$$

Substitution of (4) to (16) gives

$$0 = \rho F_i - \frac{\partial p}{\partial x^i} + \frac{\partial}{\partial x^j}\Big(\mu(\frac{\partial v^i}{\partial x^j} + \frac{\partial v^j}{\partial x^i})\Big) \tag{18}$$

Heat transfer equation (5) can be reduced to

$$c_p\rho\Big(\frac{\partial T}{\partial t} + v^i\frac{\partial T}{\partial x^i}\Big) = \frac{\partial}{\partial x^i}\Big(\kappa\frac{\partial T}{\partial x^i}\Big) + \frac{1}{2}\mu\Big(\frac{\partial v^i}{\partial x^j} + \frac{\partial v^j}{\partial x^i}\Big)^2 \tag{19}$$

Equations system (17 - 19) for (p, v^i, T) is closed by appropriate initial and boundary conditions.

4.2.3 INITIAL AND BOUNDARY CONDITIONS

At initial time moment the distributions of velocities and temperature field are defined. In the simplest case $\Omega(0) = \emptyset$.

Let us outline three parts of calculation domain boundary $\partial\Omega$. Let γ is the free boundary, Γ_0 is the boundary interval trough which molten corium is inputted and Γ is rest part of the boundary In general case $\Gamma_0 = \Gamma_0(t)$, i.e. input section may be changed during the time in accordance with experiment scenario.

At the solid boundary of the domain the conditions of impermeability and no slip are defined. It gives

$$v(x,t) = 0,\ x \in \Gamma \tag{20}$$

At the left boundary (melt input) it is naturally to define the distribution of inlet flux which is modeling by boundary condition

$$v(x,t) = v_0(x,t),\ x \in \Gamma_0. \tag{21}$$

On the free boundary of the melt two type of boundary conditions are specified. The first of them is kinematic condition which defines displacement of free boundary Let $f(x,t) = 0$ is equation of boundary motion:

$$\frac{\partial f}{\partial t} + v^i\frac{\partial f}{\partial x^i} = 0. \tag{22}$$

Dynamic conditions in the simplest way without consideration of external pressure and surface tension lead to balance of forces normal to surface:

$$-pn_i + \tau_{ij}n_j = 0, \tag{23}$$

where:
n – normal to the free surface.

Second dynamic condition is responsible for balance of forces in tangential direction and can be written analogous to (23):

$$\tau_{ij}\nu_j = 0, \tag{24}$$

where:
ν_i – components of tangential vector.

Boundary conditions for heat transfer equation are depend on regimes of cooling. For example the condition of convective heat exchange (water cooling) is enough general one.

$$\kappa\frac{\partial T}{\partial n} = \alpha(T - T_c), \; x \in \partial\Omega, \tag{25}$$

where:
T_c is temperature of surroundings.

In many cases it is necessary to taken into account radiative heat flux. Heat exchange with surroundings under water cooling and heat radiation on free surface is defined by the following conditions:

$$\kappa\frac{\partial T}{\partial n} = \alpha(T - T_c) - \sigma T^4, \; x \in \gamma, \tag{26}$$

where:
σ – Stefan-Boltzmann constant.

4.3 FILM FLOWS

To receive main equations of film flow [10] the approximation of thin layer is used, i.e. it is believed that the aspect ratio $\epsilon = d/L$ (where d - across size of region and L - characteristic longitudinal linear size) is rather small. This approximation is well known in hydrodynamics and widely used for physical-chemical modeling.

Let us specify the model of the film flow for case of axial geometry Instead of general Cartesian coordinates we shall use cylindrical one (r, ϕ, z), provided by $\partial/\partial\phi = 0$ and $v = (u, 0, v)$. Equations system of film flow in new cylindrical coordinates can be written as follows.

Continuity equation is transformed to:

$$\frac{\partial}{\partial r}(ru) + \frac{\partial}{\partial z}(rv) = 0. \tag{27}$$

Momentum equations is reduced to

$$\rho(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial z}) = -\frac{\partial p}{\partial r} + \frac{\partial}{\partial z}(\mu\frac{\partial u}{\partial z}). \tag{28}$$

Expression for pressure is given by

$$\frac{\partial p}{\partial z} = -\rho g \tag{29}$$

Heat transfer equation is transformed analogous to (28).
At the free boundary γ, where $z = h(r, t)$, we have:

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial r} = v, (r, z) \in \gamma \tag{30}$$

Besides that, the following conditions

$$p(r,z,t) = 0, \quad (r,z) \in \gamma, \tag{31}$$

$$\frac{\partial u}{\partial z} = 0, \quad (r,z) \in \gamma \tag{32}$$

take place.
It is no difficult to define boundary conditions at the solid wall Γ In cylindrical coordinates (see. fig. 1) following boundary conditions are valid:

$$u(r,0,t) = 0, v(r,0,t) = 0. \tag{33}$$

Let us transform the system (27 - 29). Equation (29) is reduced to

$$p(r,z,t) = -\rho g z + s(r,t).$$

Taking into account expression (32), we can obtain

$$p(r,z,t) = \rho g(h - z). \tag{34}$$

Substitution of (34) to (28) gives

$$\rho(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial z}) = -\rho g\frac{\partial h}{\partial r} + \frac{\partial}{\partial z}(\mu\frac{\partial u}{\partial z}). \tag{35}$$

Excluding pressure we come to equations (27), (35) for velocities components $u(r,z,t), v(r,z,t)$. This system is closed by (30) for the free boundary (function $h(r,t)$). This equations are amplified with conditions (32), (33).

5 MODELING OF MELT FLOWS IN VERTICAL TUBES

We consider down-directed flows of molten corium in vertical tubes. The length of tube L is believed to be much greater then its radius R. Phase transition phenomena are taken into account. Dynamics of corium solidification is considered at developed stage.

The flow is consider to be axisymmetrical. In cylindrical coordinates the internal part of the tube is defined by domain

$$G = \{(r,z) \mid 0 < r < R, 0 < z\}$$

The influence of melt dynamics on solidification is the following: boundary of solidified melt depends on the velocity distribution in the molten volume. Let us define the domain occupied by molten corium as G^*

$$G^* = \{(r,z) \mid (r,z) \in G, T(r,z) > T_s\},$$

where:
T_s is temperature solidus.

For description of temperature field the approximation of heat boundary layer can be used. Influence of hydrodynamics effects leads to the following energy equation.

$$C^*(T)\Big(\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial z} + \frac{1}{r}\frac{\partial}{\partial r}(ruT)\Big) = \frac{1}{r}\frac{\partial}{\partial r}\Big(r\kappa(T)\frac{\partial T}{\partial r}\Big), \ (r,z) \in G \tag{36}$$

Here:
v is longitudinal component of melt velocity,
u is transversal velocity component (for solid phase $v = u = 0$),
T – temperature,
$\kappa(T)$ – thermal conductivity coefficient,
$C^*(T)$ – specific heat capacity.

Considering the melt as two components mixture let us use following expression.

$$C^*(T) = C(T) - \lambda \frac{d\Psi}{dT},$$

where:

λ is internal heat of crystallization,

$\Psi(T)$ is volume fraction of solid phase in two component zone which is constant beyond the interval (T_s, T_l), where T_l – temperature liquidus.

For hydrodynamics processes description the Navier-Stokes equations are used in these or those approximations. As a simplest model the approximation of developed flows (Puasile flows) can be considered.

Let us write two dimensional unsteady Navier- Stokes equations for incompressible liquid with variable viscosity in cylindrical coordinates. Momentum equations can be written in form

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + v\frac{\partial u}{\partial z} = F_r - \frac{\partial p}{\partial r} + \frac{\partial}{\partial r}(2\nu\frac{\partial u}{\partial r}) + \frac{\partial}{\partial z}\left(\nu(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r})\right) + \frac{1}{r}(2\nu\frac{\partial u}{\partial r}), \tag{37}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial v}{\partial z} = F_z - \frac{\partial p}{\partial z} + \frac{\partial}{\partial z}(2\nu\frac{\partial v}{\partial z}) + \frac{\partial}{\partial r}\left(\nu(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r})\right) + \frac{1}{r}\left(\nu(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r})\right) \tag{38}$$

Continuity equation for condition of incompressibility is the following:

$$\frac{\partial(ru)}{\partial r} + \frac{\partial(rv)}{\partial z} = 0. \tag{39}$$

Here:

ν is kinematic viscosity,

F_r, F_z is components of external forces (in our case $F_r = 0, F_z = g(1 + \beta(T - T_c))$),

g is gravitational acceleration,

β – volumetric coefficient of thermal expansion.

Hydrodynamics of liquid phase of the solidifying corium is described by equations which are obtaining from the above system (37 - 39) in suggestions that the longitudinal velocity component is much greater then transversal one and the second derivative in longitudinal direction is greater then the transversal one. Omitting mixture derivatives we obtain:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial r} + v\frac{\partial v}{\partial z} = g - \frac{\partial p}{\partial z} + \frac{\partial}{\partial r}\left(\nu\frac{\partial v}{\partial r}\right), \tag{40}$$

$$0 = -\frac{\partial p}{\partial r}, \tag{41}$$

$$\frac{\partial(ru)}{\partial r} + \frac{\partial(rv)}{\partial z} = 0. \tag{42}$$

Let us assume that at tube entrance the uniform flux of molten corium is defined by

$$v(r,0,t) = V(t), u(r,0,t) = 0. \tag{43}$$

At the line of symmetry the following conditions are valid:

$$u(0,z,t) = 0,\ \frac{\partial v}{\partial r}(0,z,t) = 0. \tag{44}$$

At the solid part of the boundary ∂G^* conditions of no slip and no permeability are specified.

$$u(r,z,t) = 0, v(r,z,t) = 0, r = r^*(z,t), z > 0, \tag{45}$$

where:

$r^*(z,t) = R$, if in the section $z = \text{const}$ solid phase is not formed, and
$r^*(z,t) : T(r^*(z,t), z, t) = T_s$, if in section $z = \text{const}$ is formed.

Besides that, appropriate initial conditions at $t = 0$ are defined. For example, it can be taken as

$$u(r, z, o) = U(0). \tag{46}$$

Specific boundary conditions are added to heat transfer equation in approximation of boundary layer. At the input boundary the temperature is given as:

$$T(r, 0, t) = T^*(t). \tag{47}$$

At the symmetry axis zero heat flux is defined:

$$\kappa \frac{\partial T}{\partial r}(0, z, t) = 0. \tag{48}$$

For $r = R$ the conditions are defined by specific experiment. If the field in tube vessel is not calculated, it is possible to use the condition of convective exchange:

$$\kappa \frac{\partial T}{\partial r}(R, z, t) = \alpha(T - T_c), \tag{49}$$

where:
α – coefficient of convective heat transfer,
T_c – tube temperature.

The mathematical model (36), (40 - 49) may be used as the basis for simulation of specific experiments. It is mathematically full model. In the model the dynamics of boundary solidification is considered. Convective heat transport is taken into account. To carry out numerical modeling the specific conditions of experiment should be taken into account.

6 TEST EXAMPLES

Tree tests examples have been chosen to illustrate the capabilities of numerical methods to predict dynamics of free surface fluid. These tests are gravity oscillation of incompressible layer, Rayleigh - Taylor instability, broken dam problem.

6.1 GRAVITY WAVE

Let us consider a fluid layer existing on a flat floor under action of gravity force. At the initial time moment the velocities of fluid have the following values:

$$u = -A_0 \sin(A_k x) \exp(-A_k (Y_0 - y))$$

$$v = A_0 \cos(A_k x) \exp(-A_k (Y_0 - y))$$

Magnitude of A_0 is chosen to provide small value of initial amplitude of oscillation in comparison with the fluid depth. Length of cavity X_0 is equal to π/k, depth is $Y_0 = 2$, gravity acceleration $g = 10$.

Under action of gravity force the oscillations of the upper fluid surface are begun. Frequency of oscillations is defined by analytical expression [6]:

$$w = \sqrt{g A_k \operatorname{th}(A_k y)}$$

Discrepancy between theoretical and predicted results is found to be about 3%. The decrement of amplitude is not grater then 4% for one period. Fig. 2 demonstrate sequence of different phases of oscillations, namely one quarter, one half, three quarter and complete period of oscillations.

6.2 RAYLEIGH-TAYLOR INSTABILITY

Let us consider the evolution of incompressible fluid layer which characterizes by small amplitude of disturbance in comparison with the depth of fluid. The fluid occupies a rectangular region and exits in field of gravitational force characterized by acceleration g directed vertically upward. Initial distribution of pressure is corresponded to barometrical formula $P = \rho g h$. At free boundary the pressure is equal to zero. Calculation region is covered by uniform grid in horizontal (x) direction. Along vertical (y) direction the grid is irregular.

At the initial time moment, the velocity field has the following distribution:

$$\tilde{u} = -\sin(A_k x) A_0 \exp(-A_k (Y_0 - y)),$$

$$\tilde{v} = \cos(A_k x) A_0 \exp(-A_k (Y_0 - y))$$

appropriately coordinates x, y are:

$$\tilde{x} = x - \sin(A_k x) A_0 \exp(-A_k (Y_0 - y)),$$

$$\tilde{y} = y + \cos(A_k x) A_0 \exp(-A_k (Y_0 - y))$$

The task is solved in region which length is equal to one half of disturbance length. It is considered that the density $\rho = 1$, free fall acceleration $g = 10^3$, wave number $A_k = \pi$, disturbance amplitude $A_0 = 0.02$.

Linear stage of instability is investigated in papers [14]. At the free fluid surface the spike and bubble are formed. Transition to nonlinear stage is in accordance with the asymptotic data of layer movement. Spike moves with acceleration close to free fall one. In Fig. 3 the evolution fluid free surface is shown at the time moments $t = 0., 0.07, 0.1, 0.11$.

6.3 BROKEN DAM PROBLEM

In this test, a rectangular column of water is confined between two vertical walls. The fluid exists in hydrostatic equilibrium. Relation of fluid height to its length is equal to 2.0. Free fall acceleration is directed vertically downward perpendicular to the floor At initial time moment the right wall is removed and the fluid begin to spread laterally along the base.

Existence of two free boundaries: the upper and the right, serves a good test for calculation algorithm. Evolution of fluid shape and velocity field are show in Fig. 4 - 5. Main result comparing with experimental data is leading edge position as a function of time. Figure 6 shows a good agreement between predicted and experimental results [13].

7 CALCULATION RESULTS

Models described above have been realized in the RASPLAV/SPREAD code. We used finite element technique in Lagrangian coordinates for designing of moving meshes for solving 2-D problem and Eulerian approach for thin layer approximation. Hydrodynamics part of the code was validated on the standard test calculations like broken dam problem, gravity wave, Rayleigh-Taylor instability problem [9]. This allows to apply developed codes and to carry out hydrodynamics and heat transfer processes investigations in the spreading melt. We consider simplified problems to evaluate parameters characterizing mass and heat flow and reaching of film regime flow Both discussed above models are used for calculations. For these estimations we do not take into account reological properties of melt.

We consider simple example of axisymmetrical flow of molten material for the case of quick melting and destruction of vessel low head and flow of molten corium and construction materials. For this case we propose existence of large space for spreading without any constructions. For this scenario of LHF we shall consider also transformation of flow to film one for which results of calculations by full model will be considered as initial values.

At initial time moment the fluid has a form of cylinder with radius R_0 and height H_0. Gravity acceleration is directed vertically along z axis. Upper and right boundaries of region are free. On the left and bottom boundary we define normal constituents of velocity equal to zero. Initial distribution of velocities in horizontal and vertical directions is chosen as zero too. Due to gravity force the fluid starts its motion in both vertical and horizontal directions. One of the goals of these calculations was to investigate main tendencies and asymptotics of flow of viscous fluids, but not the simulation of real molten corium behavior.

Viscosity coefficients varied in calculations in wide range of values. The relation of maximal to minimal values was taken as 1000 to find dependencies of flow on viscosity. In predictions the model with constant viscosity was used. Value of viscosity of possible mixtures is unknown and there are no models for calculations of viscosity of $U - O - Zr$ mixtures. At the temperatures of 3100 K UO_2 has $(4-5)10^{-3}$ Pa/s, ZrO_2 – 5.610^{-3} Pa/s [12]. Thus this value is about 10^{-2} Pa/s and kinematic viscosity is about $\nu_0 = 0.01cm^2/s$. Between solidus and liquidus temperatures the viscosity may be higher for several orders of magnitude.

Initial configuration of fluid and evolution of fluid shape for the several time moments are shown in Fig. 7. It can be seen the formation of thin layer of molten fuel during the process of spreading. In Fig. 8 the dynamics of height of fluid for two fixed coordinates $r_1 = 2.5R_0$ and $r_2 = 3R_0$ is presented. During the time the height of fluid in these points reach their stationary values and flow is transformed to the developed stage. Table 1 shows the asymptotic values of height and front position for different values of viscosity.

Table 1

ν/ν_{min}	h_1/r_0	h_2/r_0	r_f/r_0
1000	0.66	0.53	3
100	0.46	0.4	3.8
1	0.43	0.33	4.2

Tendency of increasing of fluid height in the case of increasing of viscosity value is observed.

Thus, the result of two dimensional predictions demonstrates the transient stage of flow and its transformation to the film flow It gives a possibility to estimate the shape of the front of spreading fluid.

In order to calculate the quasi-steady stage of flow the approximation of thin layer is used. Flow of internally heated fluid along the basemat is considered. The profile of the basemat may be changed during the interaction process. Fig. 9 show the field of velocities in liquid layer Figures 10 - 11 demonstrate temperature behavior in two fixed points and front position versus time.

8 CONCLUSIONS

Mathematical modeling of thermal and hydraulic processes in spreading liquid layer onto the basemat is performed. To investigate behavior of flow two types of mathematical models were developed:

1) full model based on two dimensional heat transfer and Navier-Stokes equations;

2) simplified model based on approximation of thin layer. These models include such processes as: crust formation, melting and ablation of the basemat material.

Asymptotic behavior of the layer height in dependence on viscosity is found with help of two dimensional modeling.

In thin layer calculations the quasi-stationary regime of flow was obtained and studied. This model gives a possibility to predict two dimensional temperature and velocity field distribution and also to calculate evolution of height of liquid layer and front velocity

Developed models and code allow to calculate interrelated heat - and mass transfer in spreading molten core and basemat materials in accordance with appropriate boundary conditions. Boundary conditions may be chosen in dependence of scenario of modeling, for example: interaction with water at the upper boundary or heat radiation; interaction with decomposing concrete or with heat-proof ceramics at the bottom boundary.

Computer code RASPLAV/SPREAD is a sufficiently compact and flexible code which may be incorporated or linked with some another codes.

NOMENCLATURE

(r, z)	—	cylindrical coordinates;
T	—	temperature;
t	—	time;
c	—	specific heat capacity;
k	—	thermal conductivity;
$\dot{q}$	—	volumetric heat generation;
(u, v)	—	radial and axial components of velocity;
F_r	—	radial coordinate of external forces;
F_z	—	axial coordinate of external forces;
g	—	free fall acceleration;
P	—	pressure;
D	—	velocity-strain tensor.
Greek letters		
ν	—	kinematic viscosity
ρ	—	density
μ	—	dynamic viscosity coefficient
ξ	—	second viscosity

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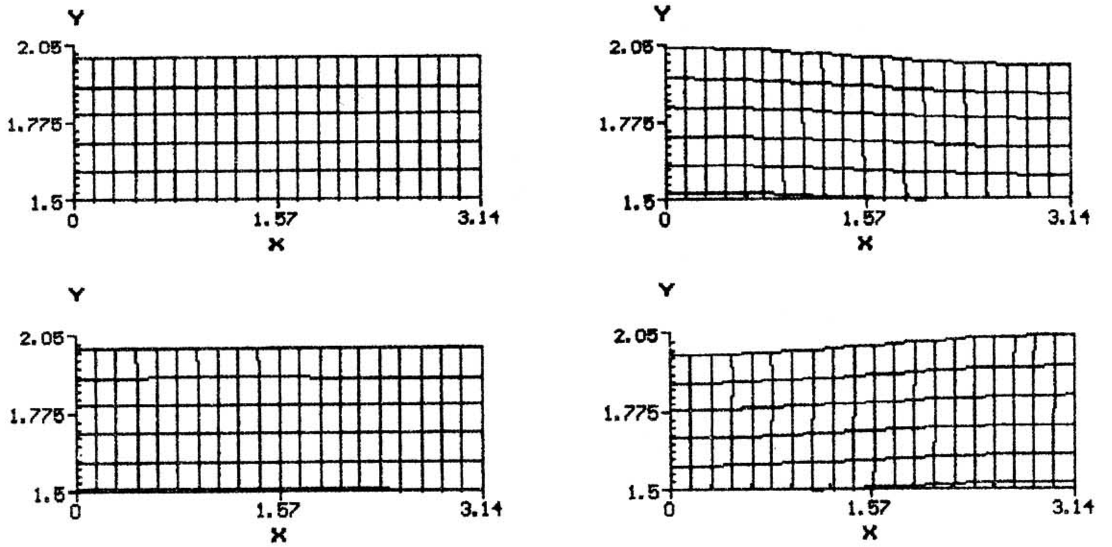

Figure 2: Gravity wave.

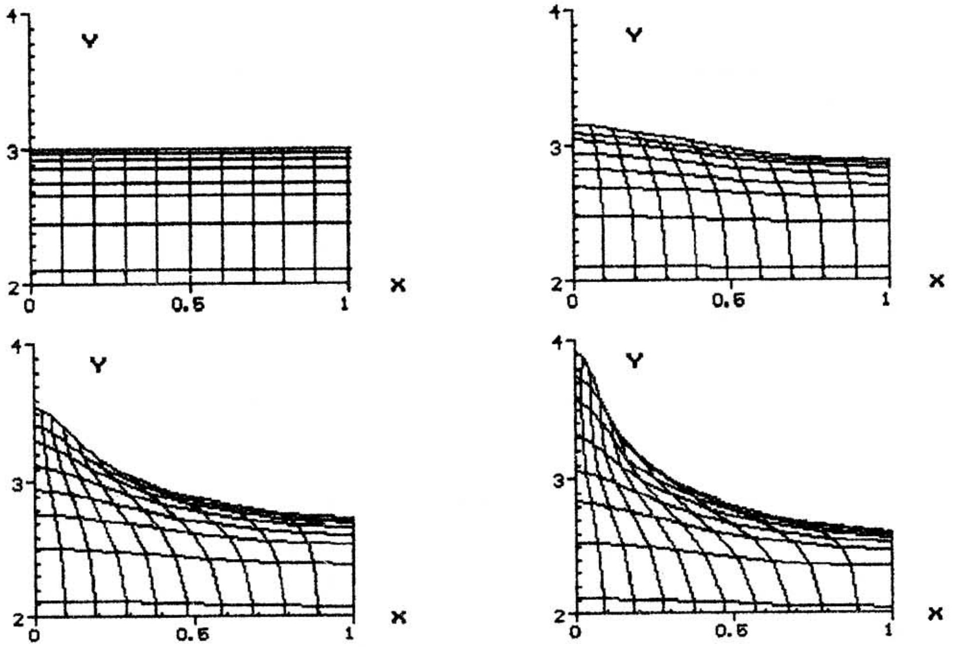

Figure 3: Rayleigh-Taylor instabilty.

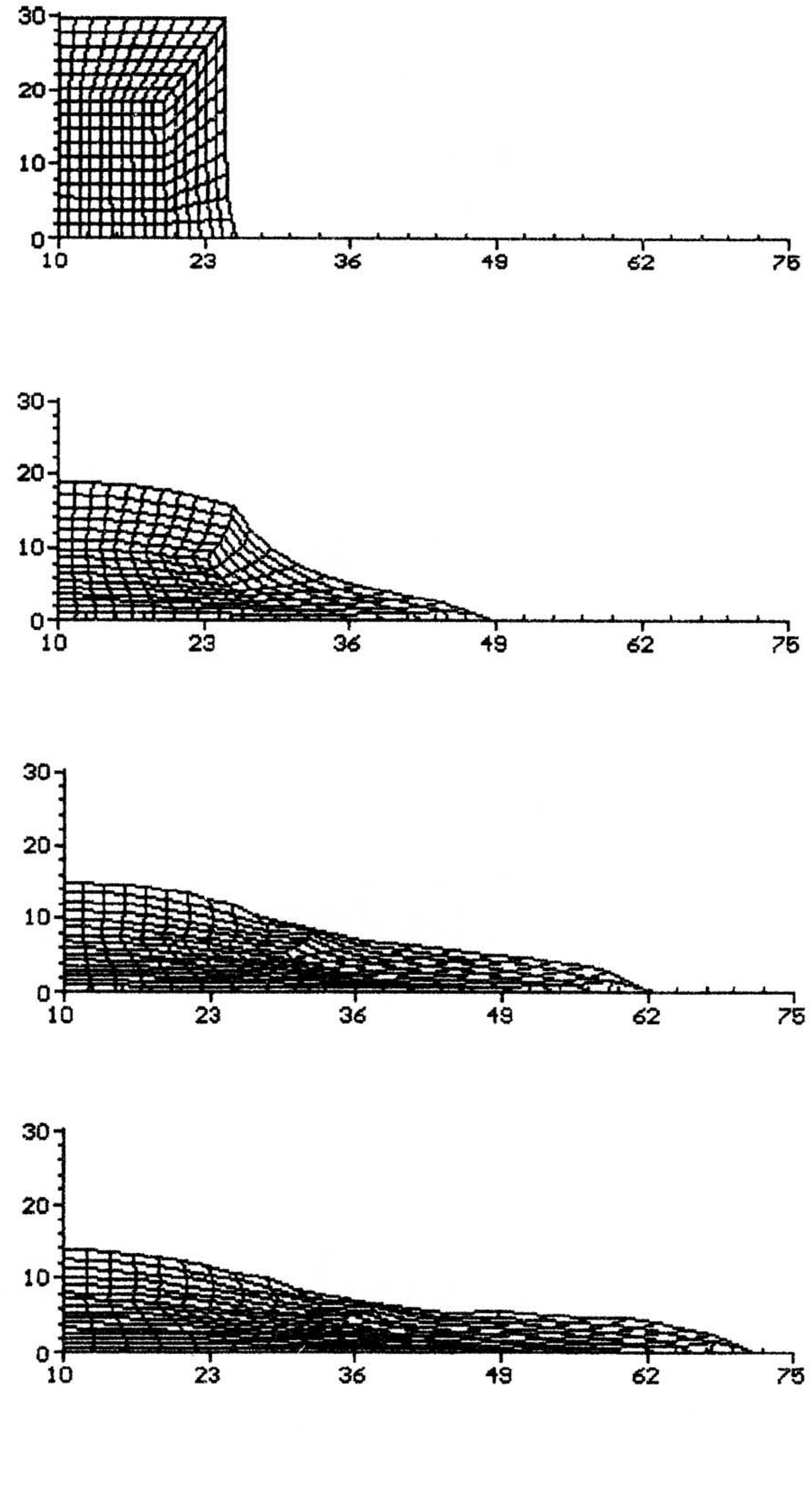

Figure 4: Broken dam problem. Fluid configuration.

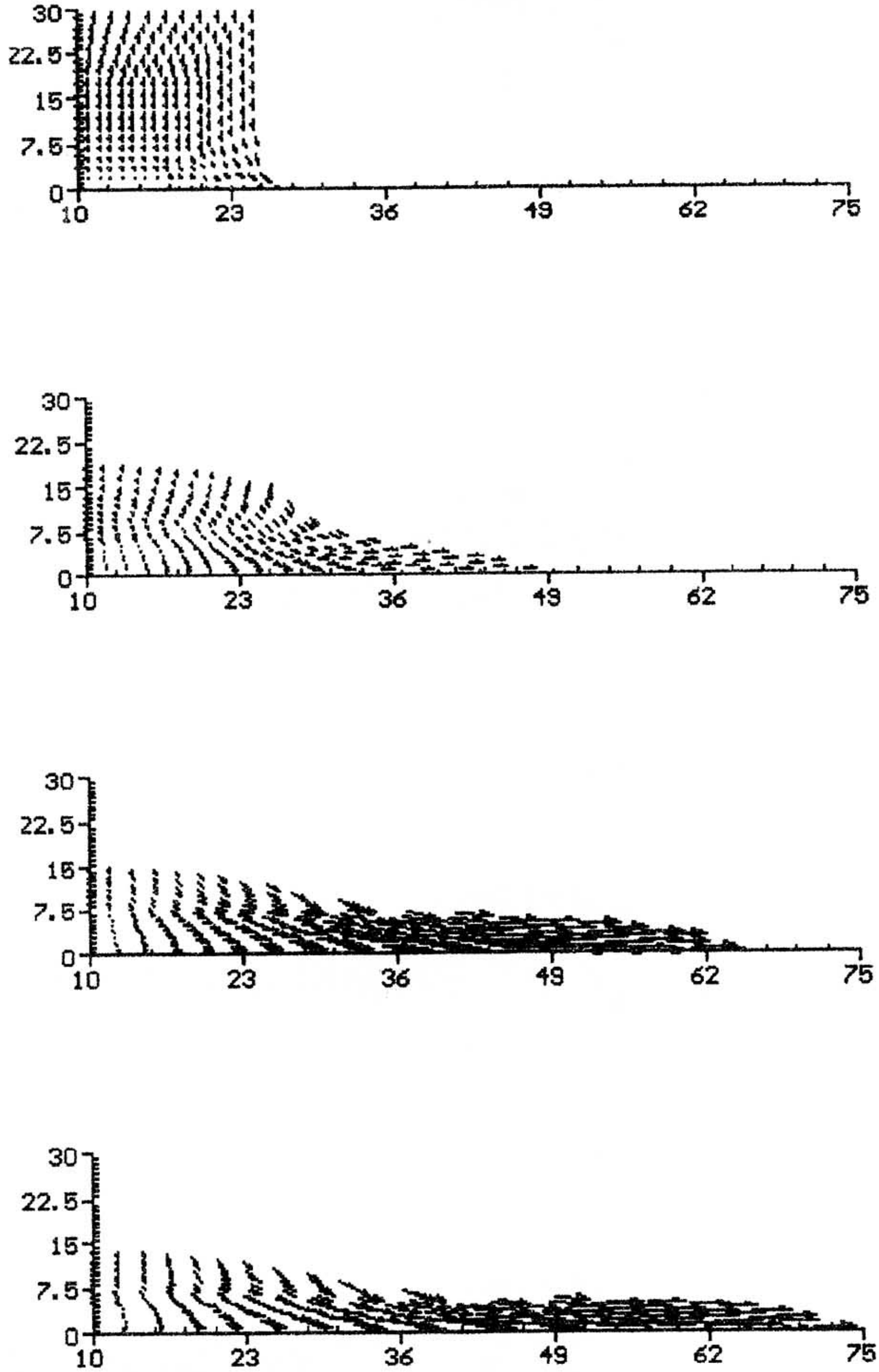

Figure 5: Broken dam problem. Velocity field.

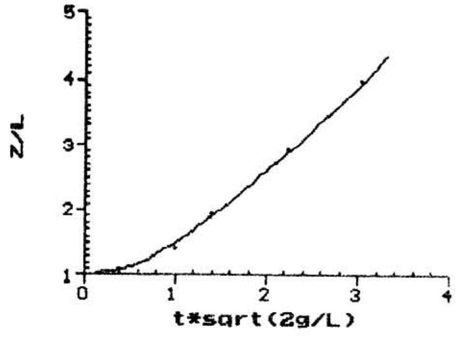

Figure 6: Broken dam problem. Leading edge position versus time.

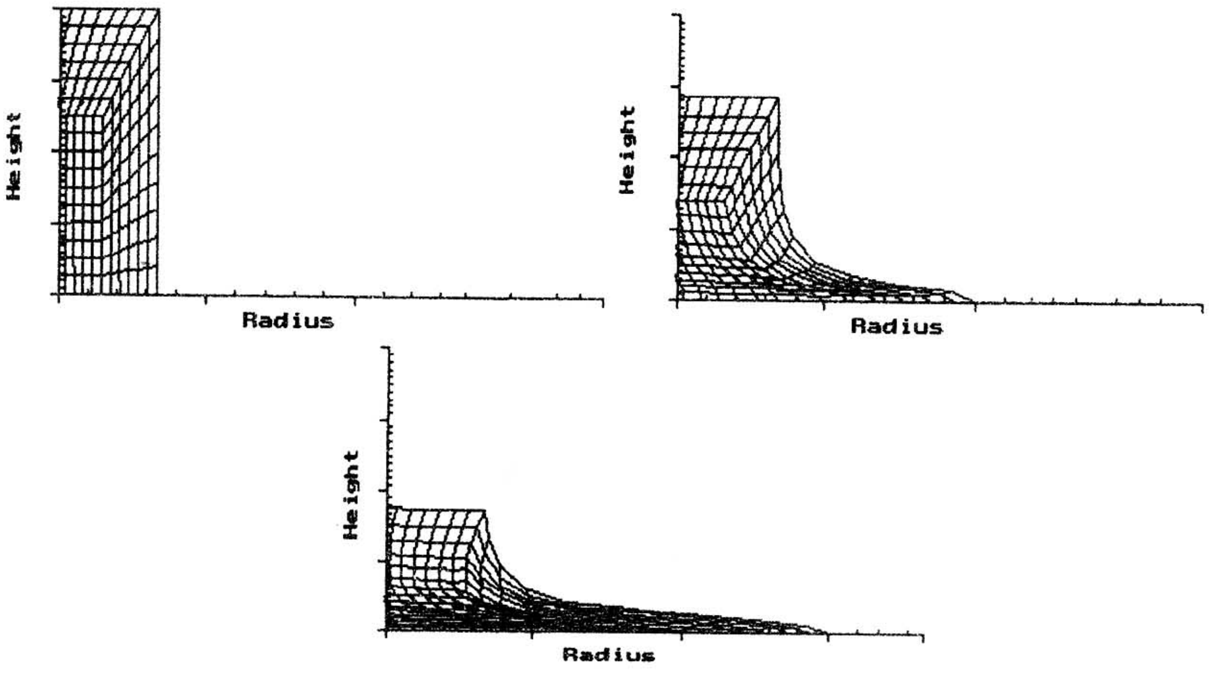

Figure 7: Evolution of fluid.

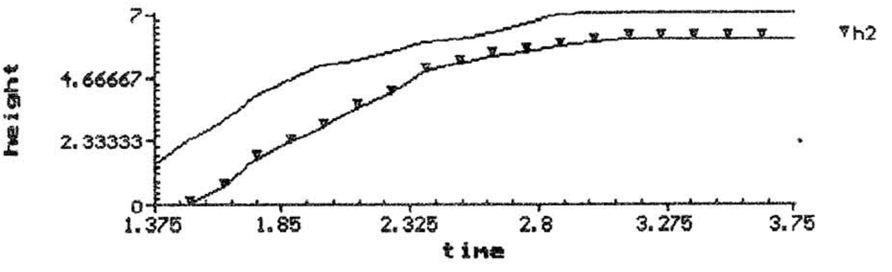

Figure 8: Height of fluid in two fixed points.

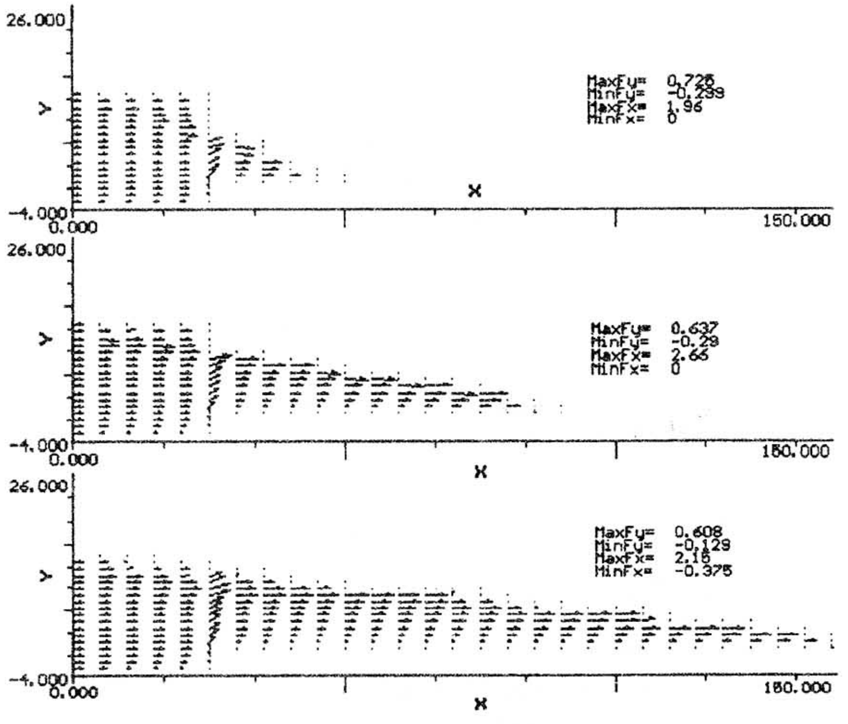

Figure 9: Thin layer Velocities field.

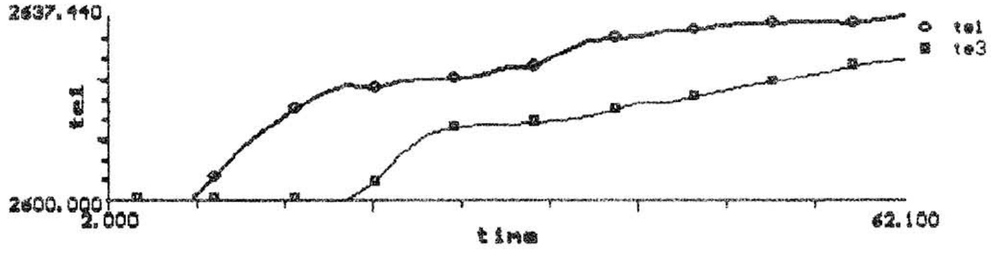

Figure 10: Temperature in two fixed points.

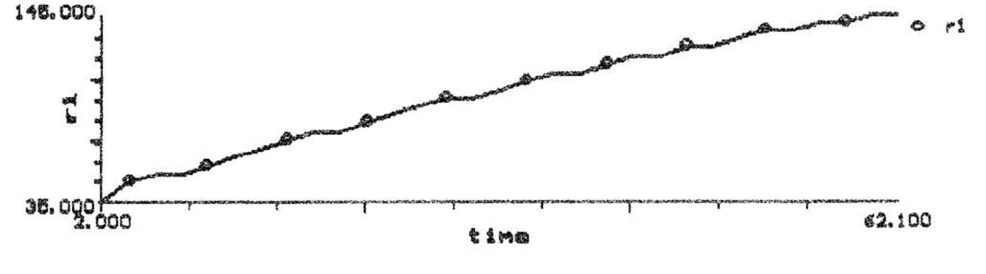

Figure 11 Position of liquid front.