High Prandtl Number (Flibe) Liquid Blanket Heat Transfer

Laminar model solution and wavy surface and turbulence consideration

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Consideration of Wavy Surface and Turbulent Liquid Blanket

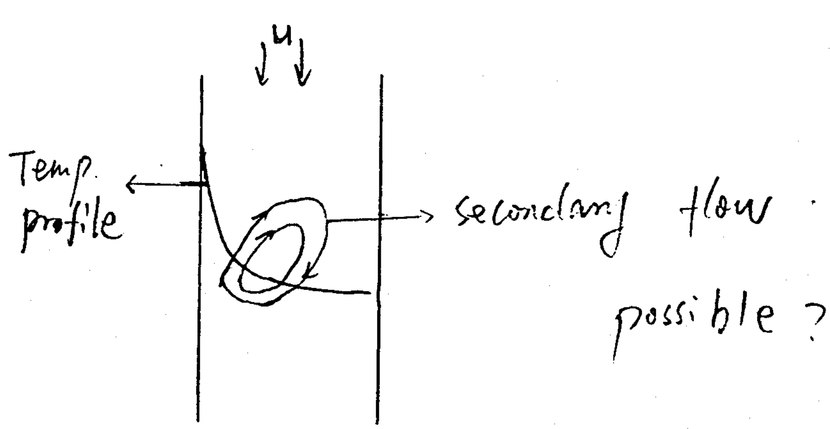
The numerical calculation result of wavy surface effect and turbulence effect on heat transfer will direct our designs of liquid jet. Levich, in his analysis of liquid film mass transfer, concluded that wave surface will enhance mass transfer by 15%. Treatment of turbulence and treatment of wavy surface are totally different in numerical computation scope. Wave here means the elastic deformation. not viberation created by turbulent eddies.

Turbulent Flow Model

• There are so many turbulent flow models. Eddy diffusivity model is to use complementary turbulence viscosity parameters and turbulent diffusivity parameters obtained from some semi-empirical equations in the momentum and energy equations to incorporate the eddy effect.
• We can also directly add eddy velocity terms to the corresponding laminar flow velocity field such as $u = U + u'$, $v = V + v'$, $w = W + w'$, then solve the energy equation again. Finding eddy velocity field (u', v' w') is quite difficult.

• Above methods are difficult to consider the convective transport of the turbulent characteristic parameters such as eddy diffusivity. For our long liquid blanket, considering this convective transport is necessary. The $K - \epsilon$ can serve this purpose. For $K - \epsilon$, we need to solve coupled momentum, energy and turbulent characteristic parameters governing equations.

• Because of the high temperature gradient, we expect that there is secondary flow in the liquid sheet that will enhance the heat transfer. We have to depend on detailed numerical computaion to see whether the secondary flow exists. In other word, the temperature will help to generate turbulence.



Wavy Surface Simulation

To consider wavy surface, all the governing equations should be in transient form, because we need to consider that boundaries change with time, and then all the parameters change with time. The general numerical methods for the free surface problems include boundary-fitted grids method, MAC(Marker-and-Cell), and VOF(Volume-of-Fluid). I can not decide which one is more appropriate to our problem. Need more investigation. We plan to first do the laminar wavy surface liquid compuation, then incorporate turlulence model in it

Problem Description

The proposed annular liquid blanket is simplified as a 2-D plane liquid sheet in some analyses

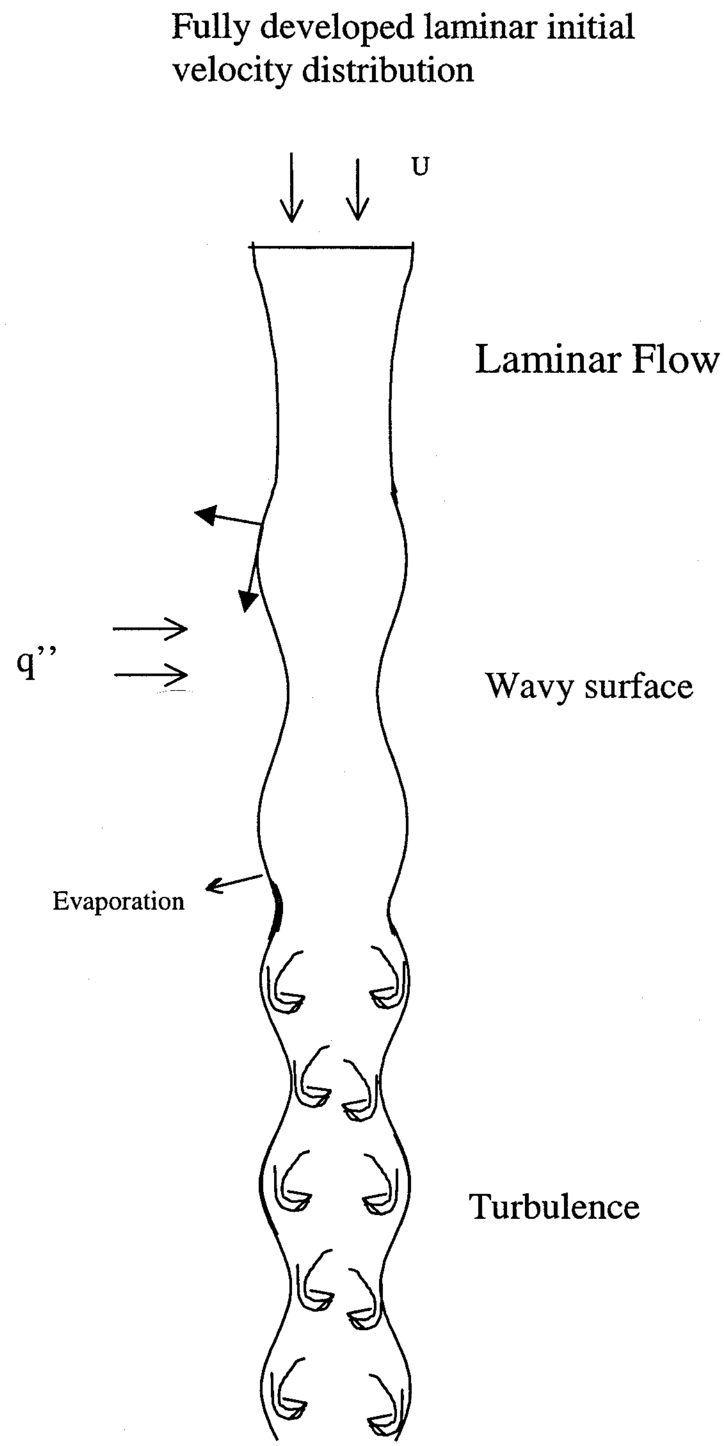


Fig. 1. Liquid blanket flow type illustration

Fig. 2. Water jet shapes at different Reynold numbers

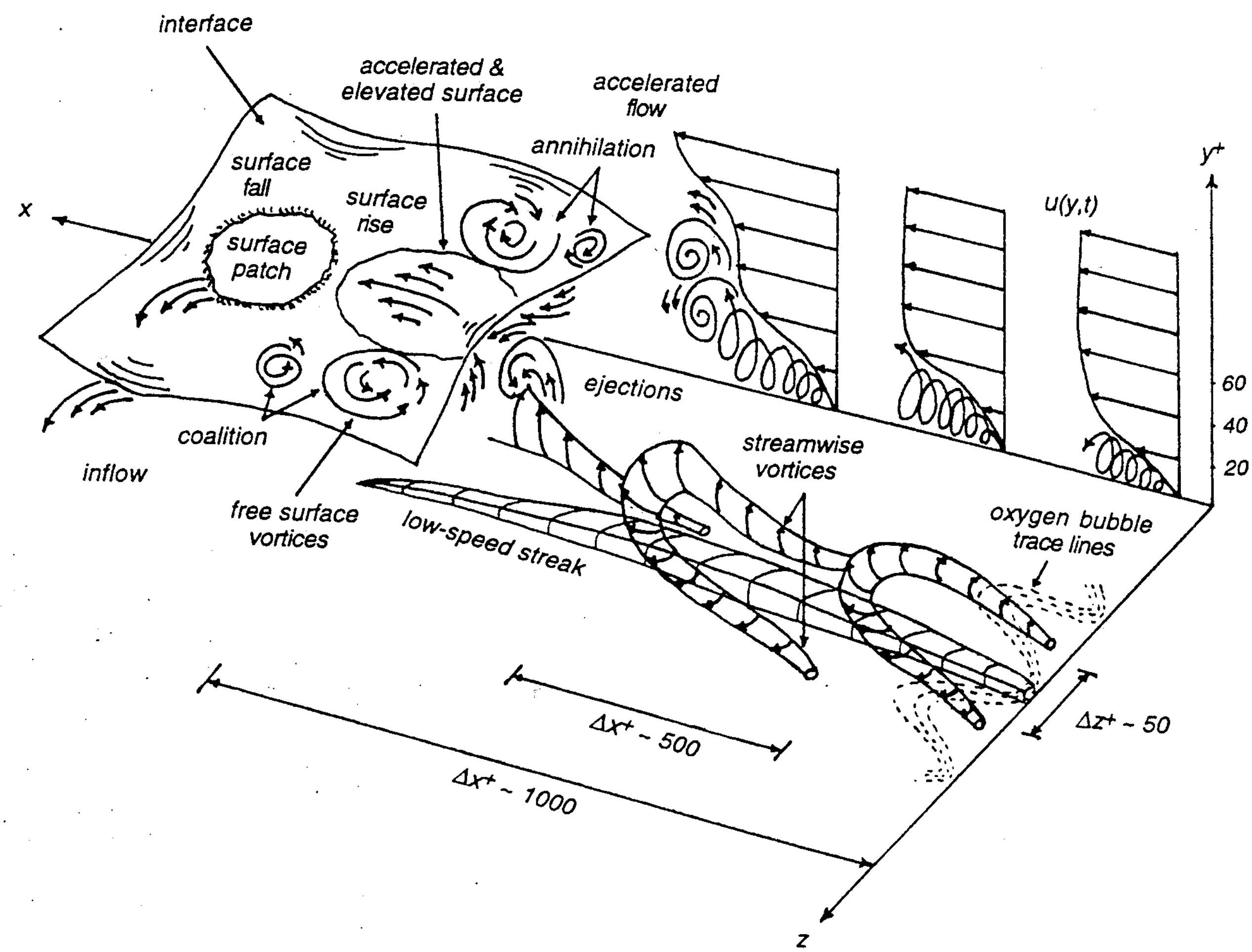


Fig. 3. Conceptual illustration of burst-interface interactions

Objective

Wavy Surface and Turbulence Structure on Heat Transfer Enhancement

Approach

1. Theoretical analysis to understand more about physical mechanism

2. Numerical simulation of wavy surface and numerical computation of turbulence effect on heat transfer

3. Compare with data from experiments to modify numerical models

This meeting, focus on

subtopics

1. Comparison of numerical solution to analytical solution in order to check computer code

2. Comparison of temperature distribution of contracted liquid blanket to that of uncontracted liquid blanket

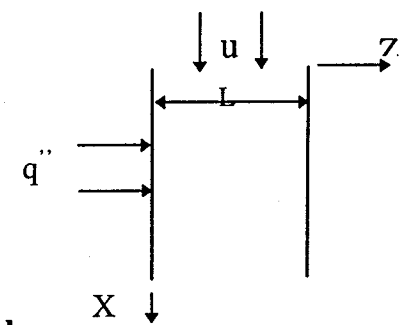
3. Wavy surface and turbulence consideration from the numerical computation point

Analytical solution for temperature distribution in idealized liquid blanket

Why study it? to get first estimation and check computer code

Idealized blanket=slug flow, no gravity effect, no contraction, no volumetric heating

There are two ways to obtain analytical solutions baced on different boundary conditions. But for our fast flow liquid jet, both work well. Sometimes for calculation convenience, we choose one rather than the other.



Energy equation:

$$u\frac{\partial T}{\partial x} = \alpha\frac{\partial^2 T}{\partial z^2}$$

Semi-infinite model

Boundary conditions:

$$-K\frac{\partial T}{\partial z} = q'' \qquad at \quad z = 0$$

$$T = T_0 \qquad at \quad z \to \infty$$

solution:

$$T - T_0 = \frac{q''}{K}[(\frac{4\alpha\frac{x}{u}}{\pi})^{1/2} e^{-z^2/4\alpha\frac{x}{u}} - z\ erfc(\frac{z}{(4\alpha\frac{x}{u})^2})]$$

Surface Temp.

$$T - T_0 = \frac{q''}{K}(\frac{4\alpha\frac{x}{u}}{\pi})^{1/2}$$

Adiabatic boundary

Boundary conditions:

$$-K\frac{\partial T}{\partial z} = q'' \qquad at \quad z = 0$$

$$-K\frac{\partial T}{\partial z} = 0 \qquad at \quad z = L$$

solution:

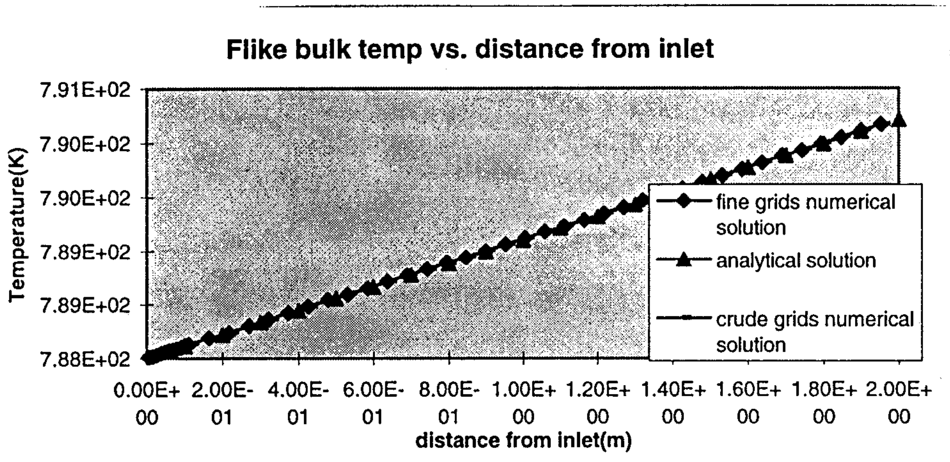
$$T = T_0 + \frac{q''(L-z)^2}{2KL} + \frac{\alpha q'' x}{LKu} - \frac{Lq''}{6K} - \frac{2q''L}{\pi^2 K}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-\frac{\alpha n^2\pi^2}{L^2 u}x)\cos\frac{n\pi z}{L}$$

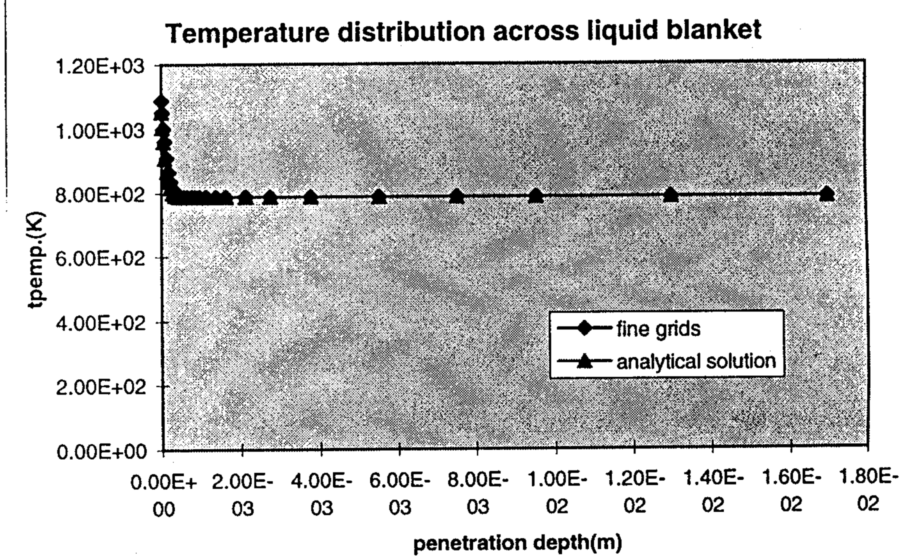
Bulk Temp.

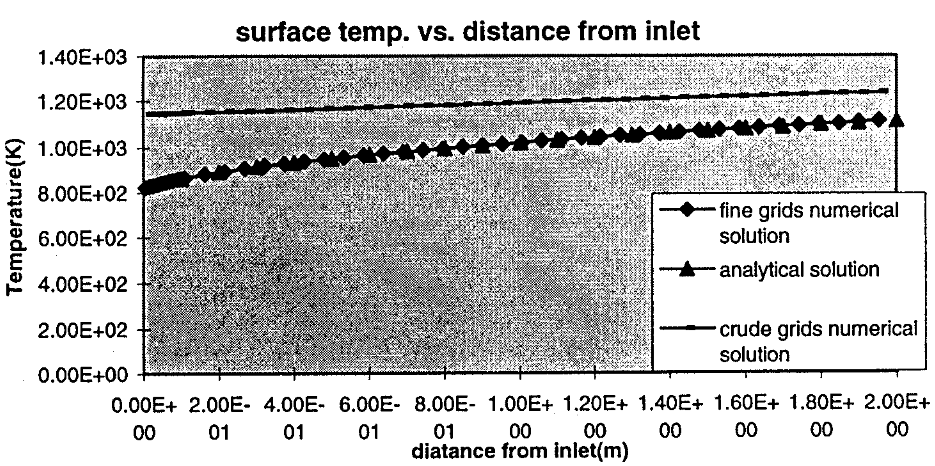
$$T_{bulk} = T_0 + \frac{\alpha q'' x}{LKu}$$

Computer code check

Comparison of the numerical solution to the analytical solution of temperature distribution of idealized liquid blanket conditions: Flibe, thickness =2cm, q''=2MW/m^2 (no volumetric heat)
velocity=20m/s, initial temp.=788K



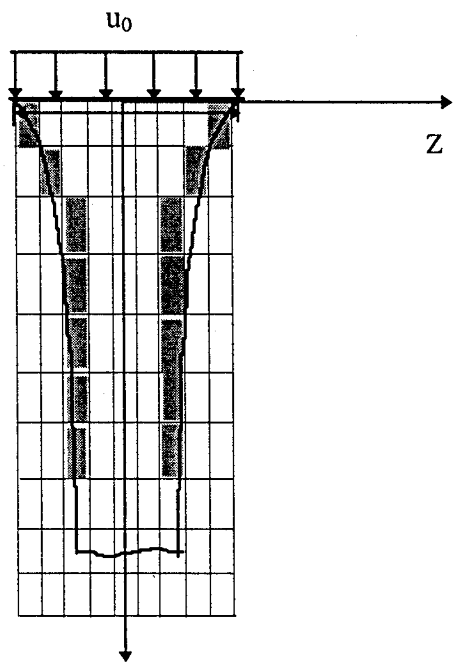




Conclusion: The basic calculation part of our code is correct. But the extent of correctness depends on the grid system. Fine grid is need for higher precise solution

How to Handle the Free Surface Boundary

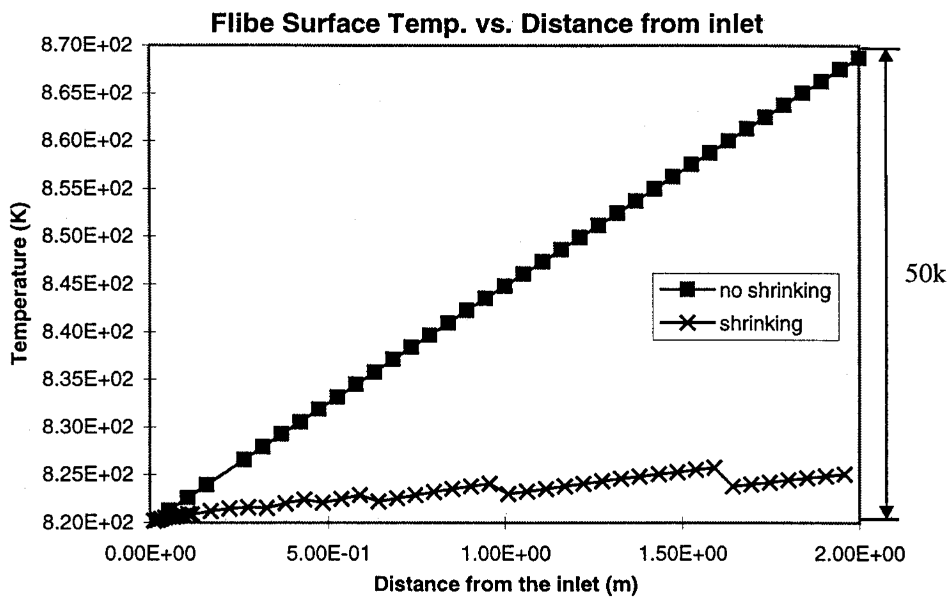
The simple way also the crude way to track free surface:
the real surface is represented by the solid curve, in numerical code boundaries are represented by the gray rectangles

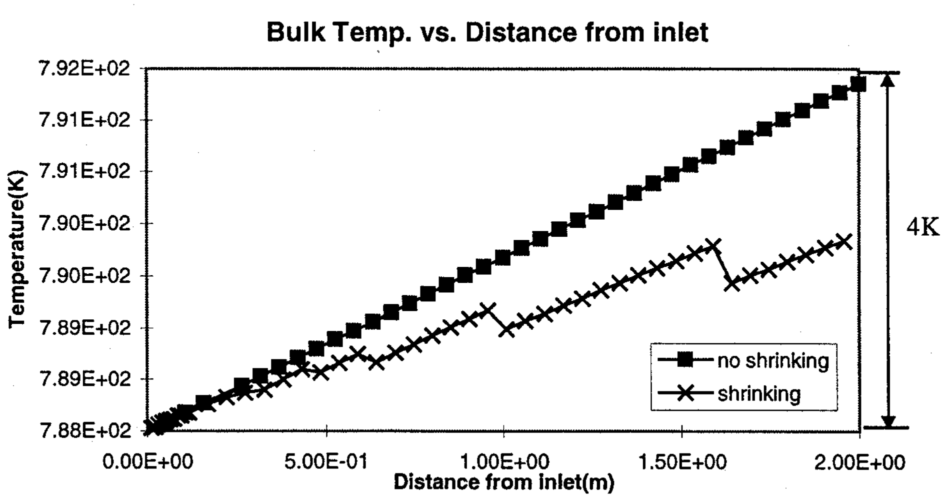


The velocity field is obtained by neglecting viscosity like solid free falling object: $u = \sqrt{u_0^2 + 2gx}$, then from control mass conservation and symmetry feature , get the velocity of z-direction

Comparison of surface temperatures and bulk temperatures for contracted and uncontracted liquid blankets

Conditions:
surface heat load=2 MW/m^2, neutron heat load=7mw/m^2,
jet initial velocity=20m/s, plane jet thickness=2cm,
inlet temp.=788K Do not consider evaporation





Conclusion: contraction do not have much effect on the bulk temperature, but have great effect on the surface temperature. This is because contraction incur velocity across liquid blanket. In other word contraction cause convection heat transfer across the liquid blanket. For low conductivity Flibe, this contribution is important. Furthermore, we can predict turbulence and wavy surface will be importance for our case.