Simple method for calculation of cryogenic transfer line cool down

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The cryogenic transfer lines operate often in intermittent mode. A software program for calculation of transient processes, especially cool down, can help to find the most economical operation parameters in some cases. A simple program based on the Mathcad-Software was developed for these purposes at Messer Cryotherm. The thermodynamic model for this program is presented and discussed.

INTRODUCTION

The objective of this work is the development of a software for estimation of cryogenic transfer line cool down time. The main requirements on this software is the simplicity and flexibility. The simplicity means clear and understandable software-syntax, so that each cryogenic engineer could be able to work with this program without special knowledge of programming language. The flexibility means that is possible to modify this software, especially for calculation of some processes or hardware configurations differing from the "standard" transfer line. Consequently the thermodynamic model & mathematics should be simple and understandable.

THERMODYNAMIC MODEL

Table 1 shows assumptions made for the development of the thermodynamic model. Figure 1 shows the calculation idea: the i- wall element has the temperature $T\_wall_i^{old}$ before the calculation step. During the calculation step *Δtime* a portion of cryogen $dM\_fluid = \dot{M}\_fluid \cdot \Delta time$ flows through the i-wall element, the temperature of this flow portion changes from $T\_fluid_i^{old}$ to $T\_fluid_i^{new}$, the temperature of the i-wall elements changes from $T\_wall_i^{old}$ to $T\_wall_i^{new}$.

TABLE 1. Assumptions

#	Assumption	Comment
1	The transfer line is long.	This assumption usually means that relationship length / diameter >> 10.
2	Radial heat conductivity of cryogen → ∞.	This assumption is valid, if the intensive mixing in every cross-section takes place. As a rule this condition is accurate for turbulent flow and areas with intensive boiling of cryogen for lines with small and medium diameter. For large transfer lines this assumption is not absolute correct and should be taken into consideration.
3	Longitudinal heat conductivity of cryogen → 0 Longitudinal heat conductivity of the wall → 0	This assumption can be accepted for long transfer line.
4	Radial heat conductivity of the wall → ∞.	This assumption means that the cooling process in the wall of inner pipe is irrelevant for present calculations method. It is because the order of magnitude for thermal diffusivity of stainless steel is

		10^{-6} m^2/sec. It means the mean transient time of less than 2 sec for 1 mm - wall, and less than 5 sec for 2 mm-wall. The typical total cool down time for a long transfer line is higher than one minute, therefore the assumption 4 can be accepted.
5	Temperature difference between cryogen and the wall is essentially larger than alteration of cryogen temperature during a calculation step for one finite element.	This assumption is valid if the finite elements are appropriate small.
6	Temperature difference between cryogen and the wall is essentially larger than alteration of wall temperature during a calculation step for one finite element.	See # 5
7	Pressure losses → 0.	
8	Cryogen is incompressible.	

The temperature change can be calculated with help of energy conservation equations for fluid (cryogen) and wall-element.

$$T\_fluid_i^{new} = T\_fluid_i^{old} + \frac{\alpha \cdot dF}{\dot{M}\_fluid \cdot Cp\_fluid}\left(T\_wall_i^{old} - T\_fluid_i^{old}\right) \quad (1)$$

$$T\_wall_i^{new} = T\_wall_i^{old} - \frac{\alpha \cdot dF \cdot \Delta time}{dM\_wall \cdot Cp\_wall}\left(T\_wall_i^{old} - T\_fluid_i^{old}\right) \quad (2)$$

These equations can be completed by mass conservation law:

$$\dot{M}\_fluid = \rho \cdot u \cdot A \quad (3)$$

For the basic version of the software the condition at the outlet was used:

$$\dot{M}\_fluid = \rho\left(T^{outlet}\right) \cdot u^{outlet} \cdot A^{outlet}$$
$$u = a\left(T^{outlet}\right) \quad (4)$$

T_fluid	- temperature of cryogen	*T_wall*	- temperature of the wall
M_fluid	- cryogen mass flow	*DM_wall*	- masse of a wall finite element (FE)
Cp_fluid	- cryogen heat capacity	*Cp_wall*	- heat capacity of the wall material
Alfa	- heat transfer coefficient	*dF*	- heat transfer surface of a FE
old	- state before calculation step	*new*	- state after calculation step
u	- velocity	*ρ*	- cryogen density
a	- sound velocity	*i*	- index of the FE
A	- cross section	*outlet*	- acc to the outlet

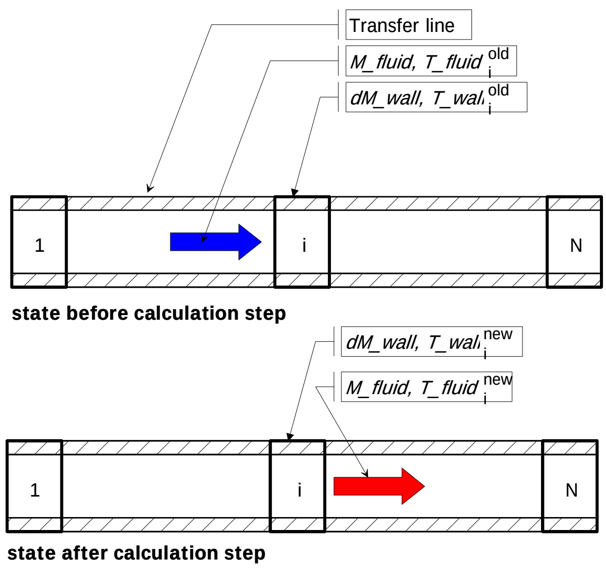

Figure 1 The principle of calculation

CRYOGEN PROPERTIES

The equations 1-4 are very simple - this set of equations can be solved directly without any iterations, if the heat capacity of cryogen and the materials is available as a function of temperature. This simplicity means advantages because of little calculation expense and decreased probability of a calculation error. These equations are correct for one-phase area only, because the heat capacity in two-phase area *Cp_fluid* → ∞. In two-phase area these equations cannot be applied. But the cool down process happens mainly in two phase area. The usual approach (to overcome the two phase- problem) is that the equations 1-4 will be completed by an additional set of equations describing the processes in two-phase area. The mathematics becomes difficult and complex. In this paper another approach will be discussed. It was assumed, that the temperature of cryogen in two phase area is not constant, but changes negligible small from boiling temperature Tb to the dew

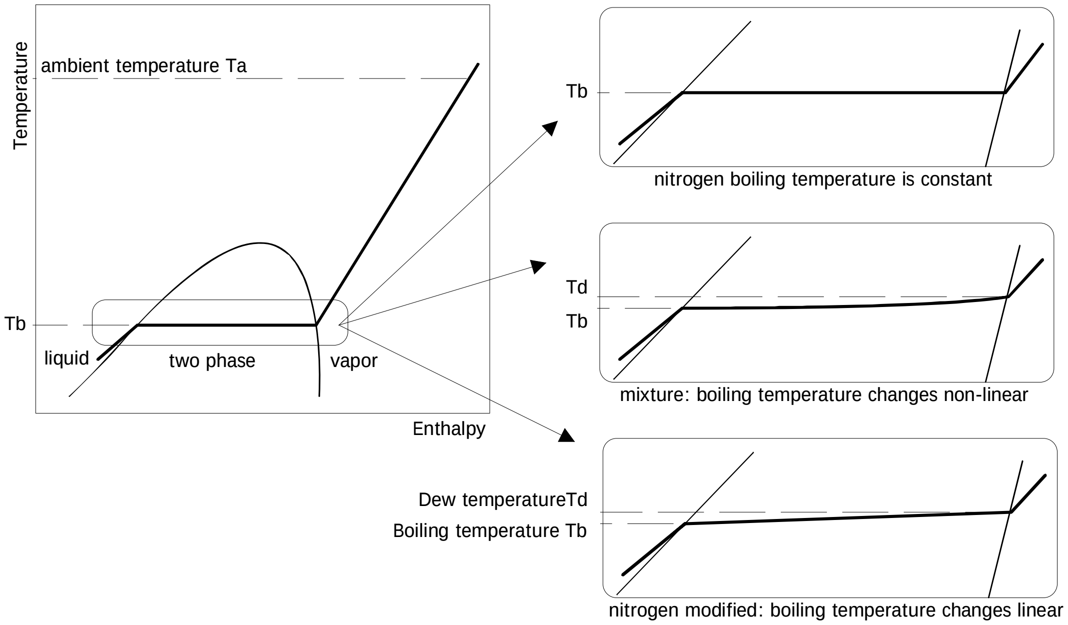

Figure 2 Cryogen properties modification

temperature Td[1], so that difference Td - Tb is negligible small (see Figure 2). This modification of cryogen properties has a consequence, that the heat capacity of cryogen are not more unlimited high and equations 1-4 are applicable in two phase area further. This clever solution helps to keep the mathematics simple and understandable.

DISCUSSION

Heat transfer coefficient and cryogen flow

The accuracy in the prediction of the heat transfer coefficient and cryogen flow in the transfer line plays decisive role in calculation of cool down time. It is because of

1. interaction of these both parameters:
   - the heat transfer coefficient depends on the flow velocity and temperature

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[1] On the first view, this assumption seems to be absurdly. On other side, we know some substances boiling at changing temperature, for example air. It is because air is not a pure substance, but a mixture of nitrogen, oxygen and other atmospheric gases. The mixture of 99% nitrogen und 1% oxygen boils at changing temperature too. But the properties of this mixture differs minimal on properties of pure nitrogen. And the cool down of a transfer line cooled by liquid nitrogen and the cool down of the same line cooled by mixture of 99% nitrogen und 1% oxygen are very similar. This fact is used in the present model.
Moreover to simplify the description of cryogen properties further, it was assumed, that the boiling temperature changes linear in two phase area between Tb and Td. All other properties are equivalent to nitrogen properties.

- the flow depends on the temperature of the cryogen at the outlet, and this temperature depends on the heat transfer inside the transfer line directly.

2. two phase heat transfer, both the heat transfer coefficient and cryogen flow can vary considerably in two phase area:
   - heat transfer coefficient from 100 to some 1000 W/(m^2-K),
   - the change of the flow velocity can amount to three orders of magnitude, because of huge density alteration in two phase area.

Therefore it is necessary to include the calculation methods for forced convection heat transfer as well as for film- and forced convection boiling in the model. Some of these methods are described in [1] and can be recommended to use.

Software Check

A very simple method to check the software for write errors is the calculation of a very long transfer line (l/d >> 10^4). For such a long lines the cryogen outlet temperature is near to ambient for relative long period of time. During this time

- the outlet conditions are constant, therefore cryogen flow is constant
- the whole enthalpy of cryogen is used for cooling purposes independent on heat transfer coefficient.

Therefore the total cool down time is close to the

$$cool\ down\ time = \frac{M\_w \cdot Cp\_w \cdot (Tambient - Tb)}{\left(\rho \cdot a \cdot A^{outlet}\right)_{Ta} \cdot \left(h^{liquid} - h^{Ta}\right)} \qquad (5)$$

Tb	- boiling temperature of cryogen	Ta	- ambient temperature
h^{liquid}	- enthalpy of liquid cryogen	M_w	- masse of the wall
h^{Ta}	- enthalpy cryogen at ambient temperature	Cp_w	- heat capacity of the wall material
A^{outlet}	- cross section	ρ	- cryogen density
a	- sound velocity		

SUMMARY

A simple method calculation of transfer line cool down was developed. A new approach for description of cryogen properties is presented. It was assumed, that the temperature of cryogen in two phase area is not constant, but changes negligible small from boiling temperature Tb to the dew temperature Tb. This solution helps to keep the mathematics simple and understandable.

LITERATURE

1. A.R.Hasan, K.A.Haque, A.S.M.Rokanuzzaman and M.M.Hasan, “Modeling of cryogenic transfer line cool down”, in *Advances in Cryogenic Engineering, Volume 45A*, Plenum, New York, 2000