Vacuum Cooling of Liquids

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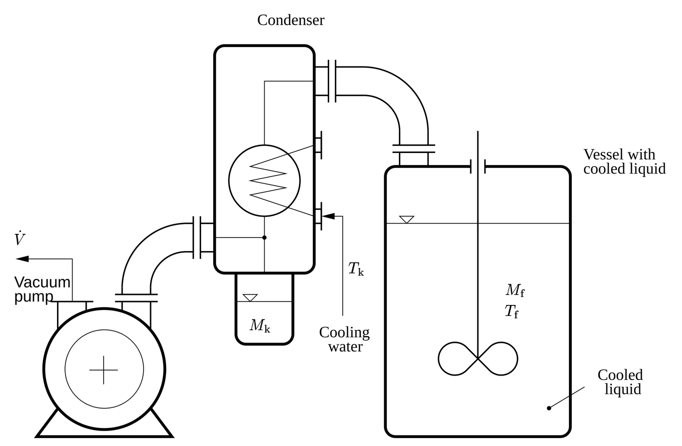

Fig. 1: Scheme of the vacuum cooling equipment for liquid products.

1 Abstract

Vacuum cooling is very often used when a fast temperature decrease of products is required. Particularly food industry, pharmaceutics and other areas take advantage of a fast cooling process which reduces high temperature effects and minimizes the time during which can occur, for example, increased growth of microorganisms. The basic principle of vacuum cooling consists in removing of the latent (evaporating) heat of a solvent (usually water), which implies a fast decrease of the cooled liquid temperature. To keep the evaporation process running, continual reducing of the total pressure in the equipment must be applied.

This paper describes a simple mathematical model of a vacuum cooling process which is based on unsteady heat and mass balances of inert gases and solvent vapours inside the equipment. The model of evaporization applies a common principle in the mass transfer theory, where an amount of the evaporated solvent is proportional to the mass transfer coefficient and the concentration gradient above the liquid phase surface. Our mathematical model enables to predict a temperature evolution regarding an equipment size, vacuum pump parameters and properties of the cooled liquid.

2 Mathematical model

- We will suppose that equilibrium exists between the surface of the cooled liquid and its vapours. Further, the surface temperature of the liquid is given by its equilibrium value which corresponds to the pressure of saturated vapours, which might be for the case of solutions increased by a physico-chemical depression.
- We consider non-ideal thermophysical and transport properties of the liquid phase, resulting in a certain resistance against the heat and mass transfer on the route towards the gas–liquid interface. This resistance prevails on the side of cooled liquid.
- The system is adiabatic, that is no heat between inside and outside of the system is exchanged.
- We neglect pressure drops and we consider that a uniform value of the total pressure p fills up the entire space of the equipment. Further assumptions reads that only saturated water vapours and no inert gases (air) can be found in the space V_w above the surface of the cooled liquid. In the condenser space, there is a mixture of water vapours and inert gases at the temperature T_K which is equal to the temperature of the water in the condenser (ideal condenser).
- The liquid phase is also considered ideally mixed with uniform temperature and concentration profiles in a whole volume except a thin layer near the gas–liquid interface, where the substantial thermal and mass resistances are concentrated as described by the film theory.

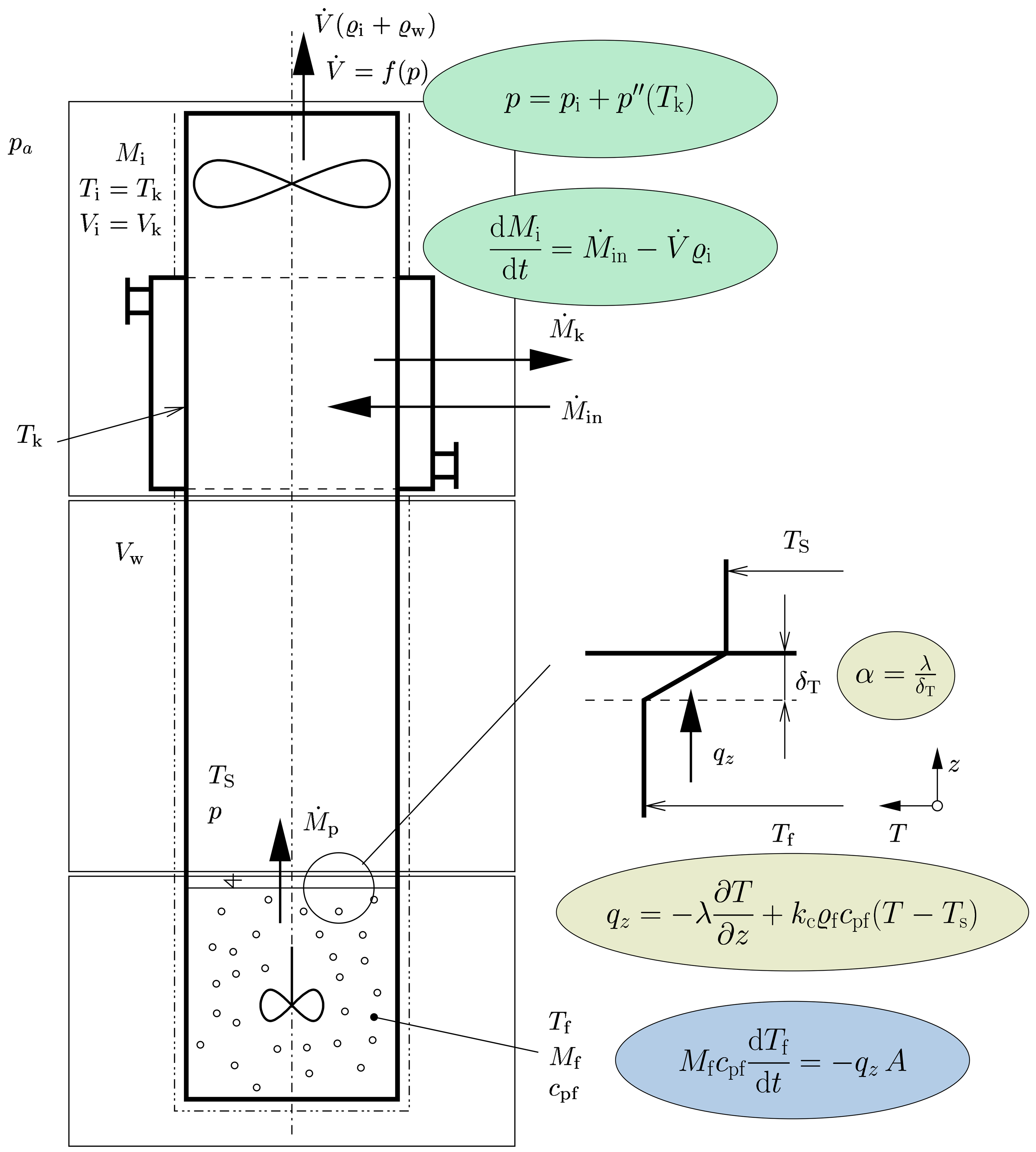

Fig. 2: Mathematical model.

3 Parameter identification

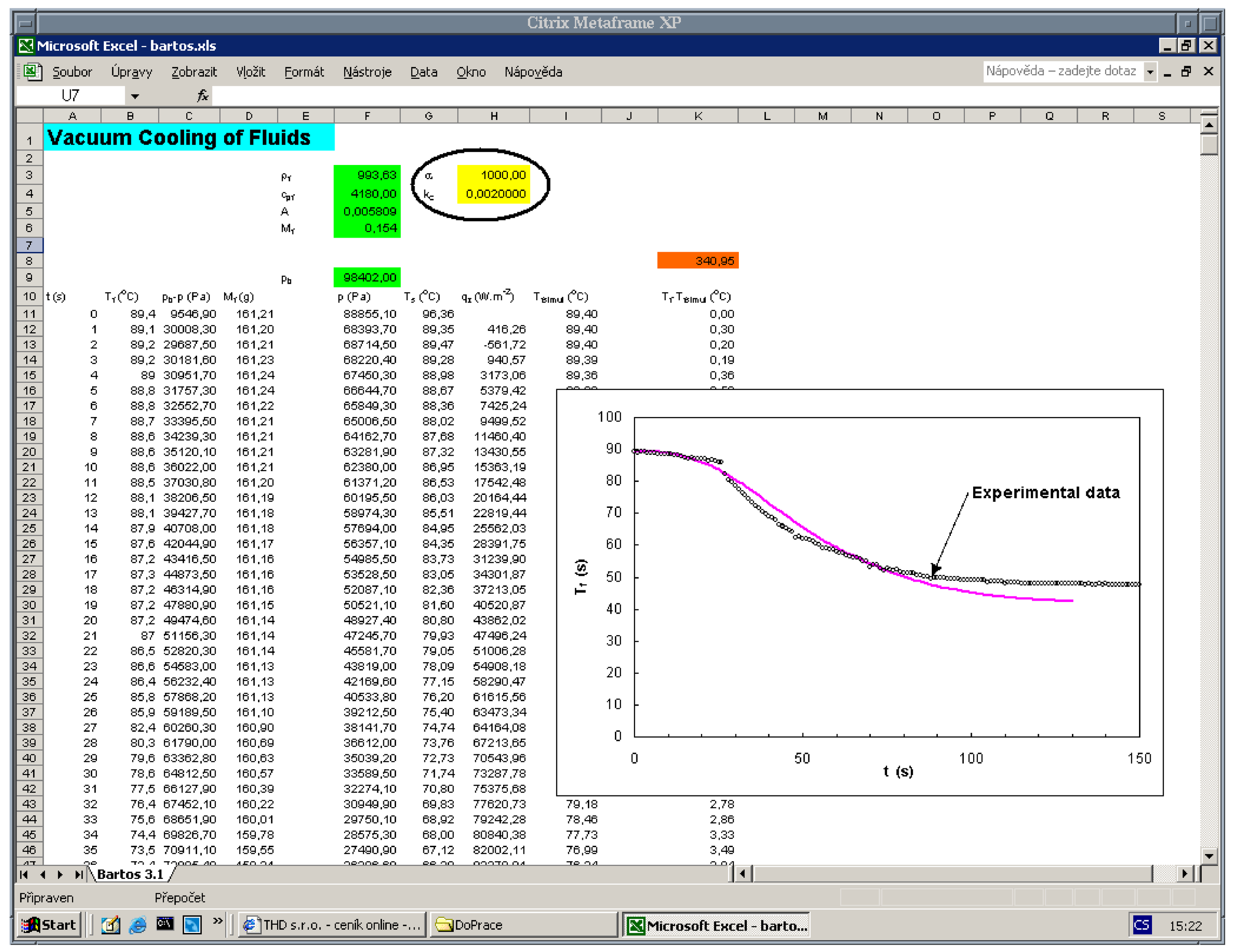

Fig. 3: Identification of the mathematical model parameters based on experimental data by Bartoš (1998).

4 Numerical simulation

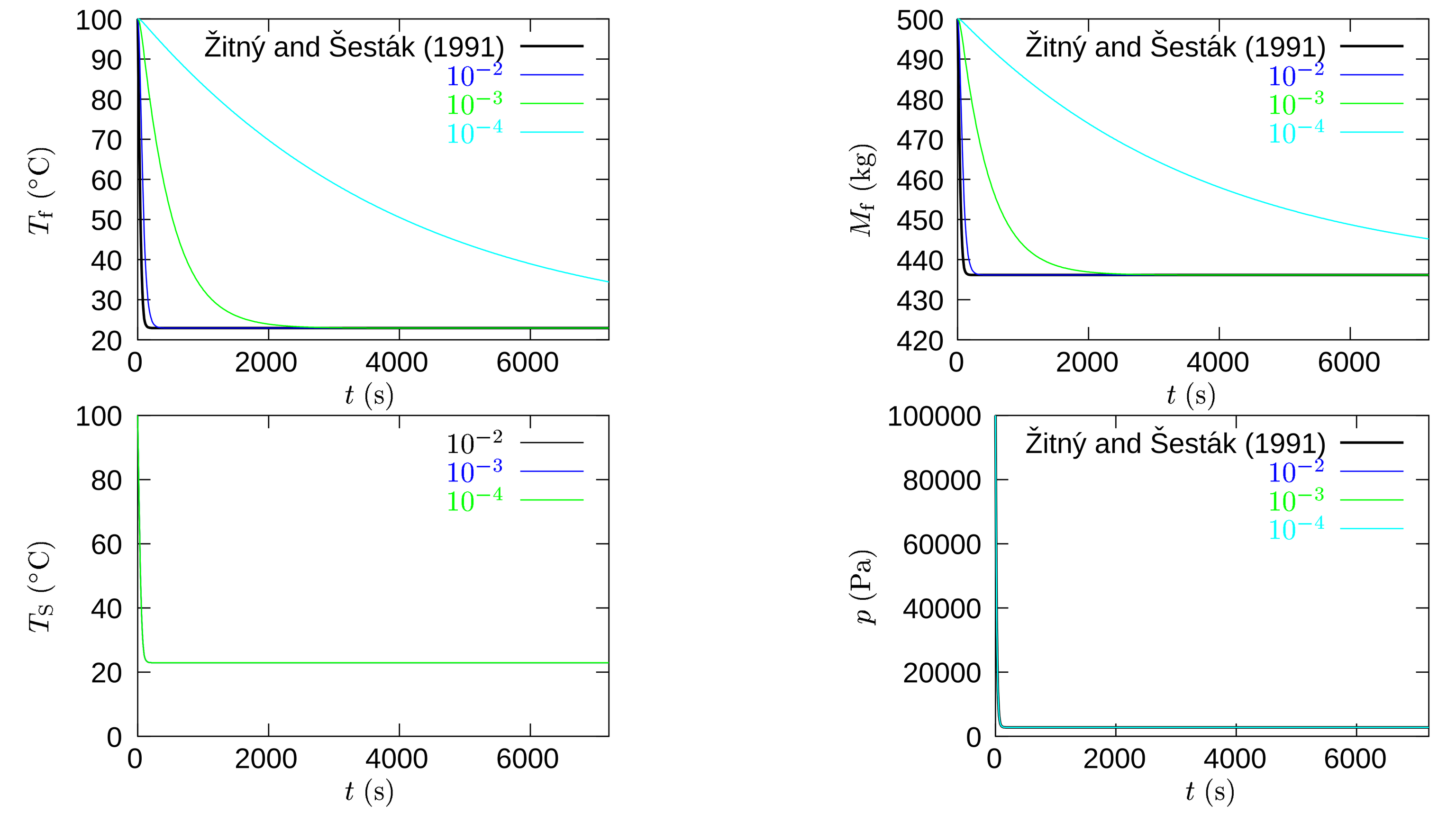

Fig. 4: Results of our numerical simulations for the values of mass transfer coefficient $k_c = 0.01,\ 0.001,\ 0.0001\ \mathrm{m^2.s^{-1}}$. Complete set of parameters can be found in the full text of this paper.

Nomenclature

A	gas–liquid interface area $(\mathrm{m^2})$
c_{pf}	specific heat capacity of cooled liquid $(\mathrm{J\,kg^{-1}\,K^{-1}})$
k_c	mass transfer coefficient $(\mathrm{m\,s^{-1}})$
M_f	mass of cooled liquid (kg)
M_i	mass of inert gases (kg)
$\dot M_{in}$	mass flow rate through leaks $(\mathrm{kg\,s^{-1}})$
$\dot M_k$	mass flow rate of condensed vapours $(\mathrm{kg\,s^{-1}})$
$\dot M_p$	mass flow rate of liquid vapours $(\mathrm{kg\,s^{-1}})$
p	total pressure (Pa)
p_a	ambient atmospheric pressure (Pa)
p_i	partial pressure of inert gases (air) (Pa)
p_w	partial pressure of liquid vapours (Pa)
p''	pressure of saturated vapours (Pa)
q_z	heat flux $(\mathrm{W\,m^{-2}})$
t	time (s)
T	temperature $(\mathrm{°C, K})$
T_e	ambient temperature $(\mathrm{°C, K})$
T_f	temperature of cooled liquid $(\mathrm{°C, K})$
T_i	temperature of inert gases (air, non-condensable gases) $(\mathrm{°C, K})$
T_k	temperature of cooling water in condenser $(\mathrm{°C, K})$
T_s	saturation temperature at pressure p $(\mathrm{°C, K})$
V_i	volume of inert gases $(\mathrm{m^3})$
V_k	volume of condenser $(\mathrm{m^3})$
V_w	volume of liquid vapours above the cooled liquid $(\mathrm{m^3})$
$\dot V$	volumetric flow rate of inert gases and liquid vapours through vacuum pump $(\mathrm{m^3\,s^{-1}})$
z	coordinate (m)
α	heat transfer coefficient $(\mathrm{W\,m^{-2}\,K^{-1}})$
δ_T	film thickness (m)
λ	thermal conductivity of cooled liquid $(\mathrm{W\,m^{-1}\,K^{-1}})$
ϱ_f	density of cooled liquid $(\mathrm{kg\,m^{-3}})$
ϱ_i	density of inert gases $(\mathrm{kg\,m^{-3}})$
ϱ_w	density of liquid vapours $(\mathrm{kg\,m^{-3}})$

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