

ration rate is assumed to be related to the large amplitude of the drop. A simple, semi-empirical modification of the model lumps the effects of internal circulation into "effective" Sherwood number and uses modified correlation coefficients for enhanced mass transfer in the gas phase is compared with the experimental data.

## 2. EVAPORATION MODEL

- \* one-dimensional, spherically symmetric evaporation
- \* single drop, assumed spherical through its lifetime
- \* initially uniform temperature distribution in the liquid phase at the start of evaporation
- \* temperature and pressure of the external gas is constant (infinite environment) or constant (finite external gas volume) depending on the evaporation history (finite external gas volume)
- \* the gas properties are calculated using so called "effective" temperature

The external heat flow rate  $dQ_e/dt$  absorbed through the drop surface is equal to the rate of change of drop internal energy  $dQ_i/dt$  plus the rate of energy used for evaporation  $dQ_l/dt$  of volume of the liquid  $dQ_l/dt$ , i.e.:

$$dQ_e/dt + dQ_i/dt + dQ_l/dt = dQ_{sum}(T_s)/dt = 0.$$

$T_s$  is the temperature at the drop surface.

The history of the evaporating drop is calculated iteratively, step-by-step, using the external temperature distribution  $T(r, t)$ , relative drop velocity  $V(t)$  and the properties of the gas and liquid in both phases.

distribution (Carslaw & Jaeger). Hence, the surface temperature  $T(r = R)$  and the vapour pressure  $P_s(t)$  are functions of time and they are recalculated for each time step  $t_i$ , using the temperature function. This is the most time consuming step of the present model. The evaporation rate is calculated with help of a multirange model of Gyranova et al. (2017). The present case reduces to Maxwell-Stephan model for diffusive evaporation :

$$dm/dt = \frac{2\pi R(t)D\rho_\infty Rm(\overline{P}v_\infty - \overline{P}s(t))Nu_M(t)}{Rv(1 - \overline{P}v_\infty)}$$

Dashed symbols indicate normalization with the ambient pressure  $P_\infty$ ,  $D$  is the diffusion coefficient,  $v_\infty$  - vapour pressure in the infinity and  $\rho_\infty$  - gas density in the infinity.  $Rv$  and  $R$  are the universal and gas constants.

The modified Nusselt number for the mass transfer (Sherwood number) depends on the Schmidt number  $Sc$ , Reynolds number and normalized gas pressure  $Pg_\infty$ :

$$Nu_M = 2(1 + 0.3Re^{\frac{1}{2}}Sc^{\frac{1}{3}}\overline{P}g_\infty^{\frac{1}{3}})$$

## 2.2 Effect of drop oscillations

Following modifications of the model are applied:

Internal circulation  $\implies$  "Effective Conductivity Model":

$$\lambda_{osc} = \lambda(1 + \chi(Re_l Pr_l)^{\frac{1}{2}}), \text{ where } \chi \text{ is found to be } 0.08.$$

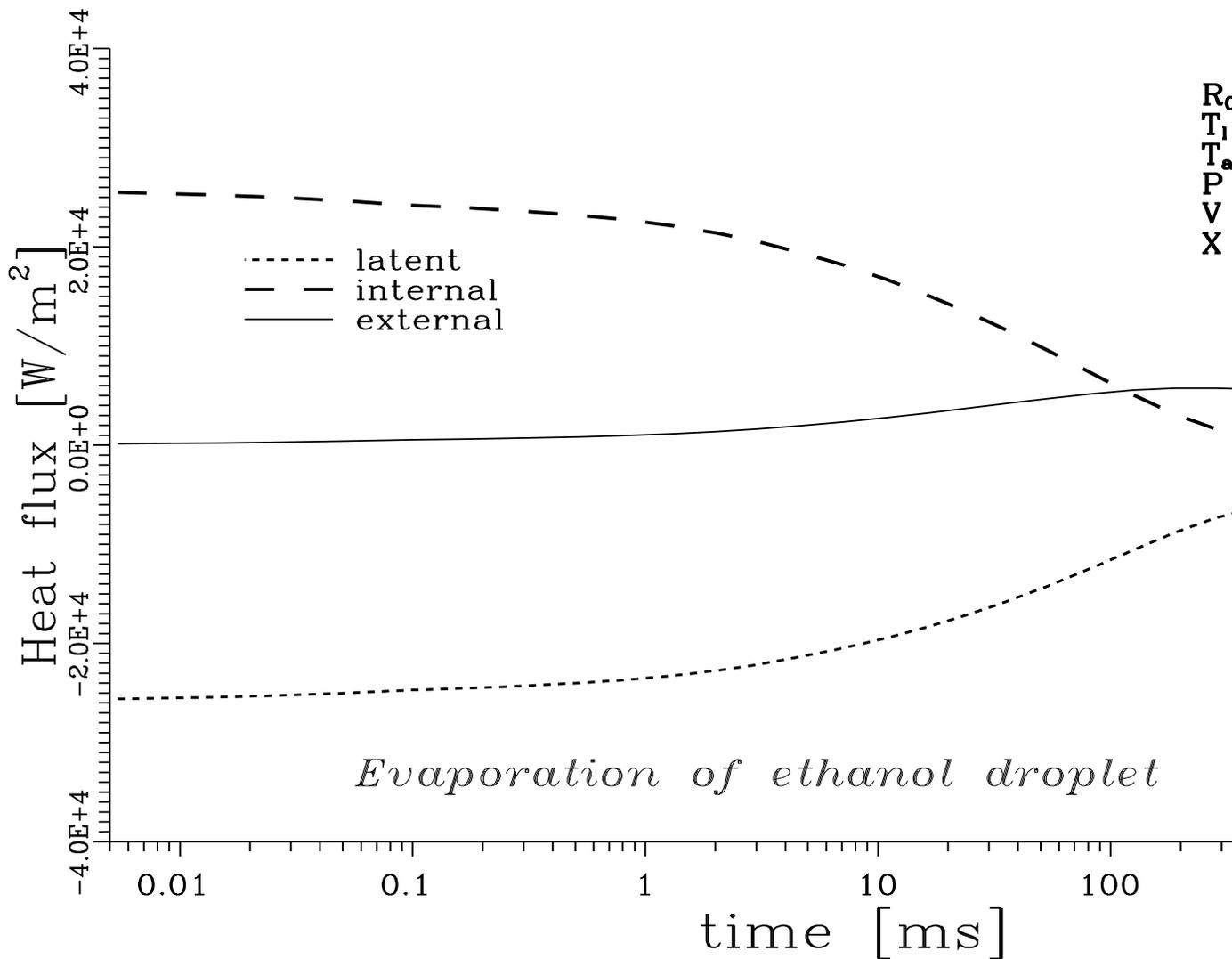
Enhanced heat and mass transfer to the gas  $\implies$  Modified correlations for Sherwood numbers:

$$Nu_{osc} = Nu(1 + \zeta Re_g^{0.7} Pr^{\frac{1}{3}}), \text{ where } \zeta \text{ is found to be } 12.5.$$

$Re_l, Re_g$  are Reynolds numbers for the internal and external flow, generated



**Figure 1** shows an example of calculated history of ethanol drop evaporating pressure. The initial drop radius is  $210 \mu m$  and initial temperatures of the drop and gas are equal  $295 \text{ K}$ . The drop initial velocity is  $10 \text{ m/s}$ . The calculated variables with time is shown together with its surface temperature and evaporation rate.

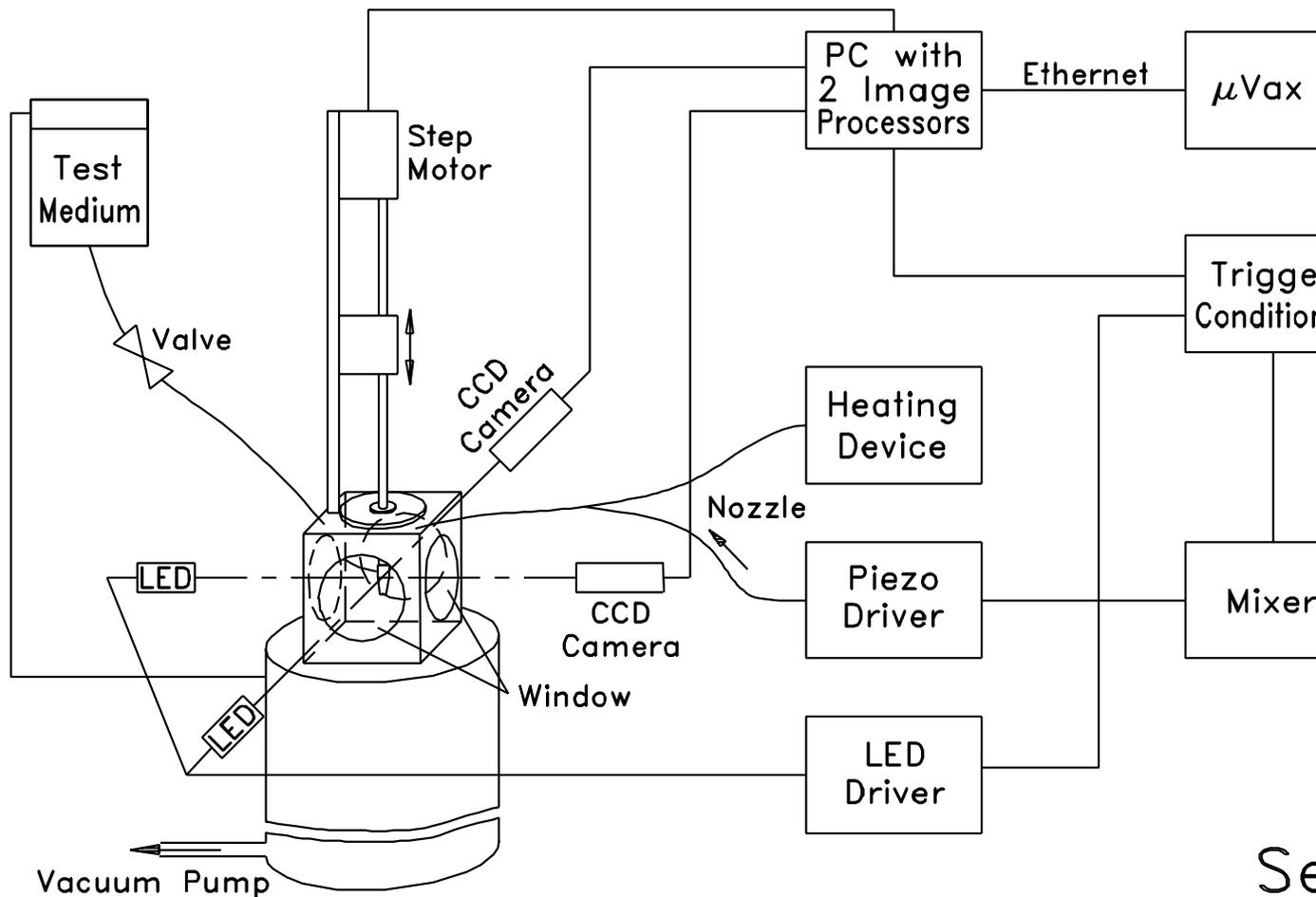


**Fig. 2.** Temporal variation of the internal, external and latent heat fluxes from figure 1.

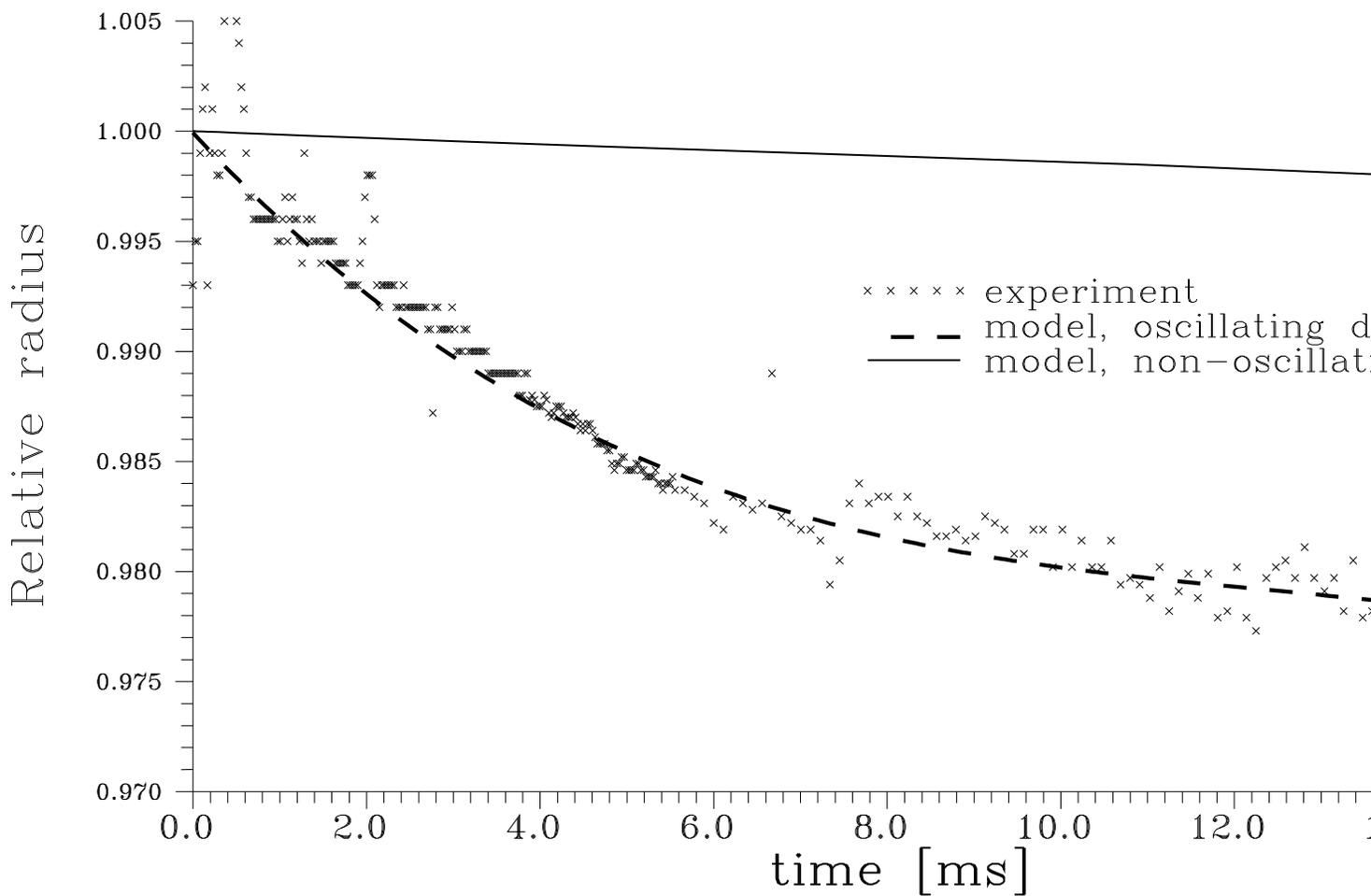
0.00      0.20      0.40      0.60      0.80  
 Radius

**Fig. 3.** *Development of the temperature distribution in the drop from figure*

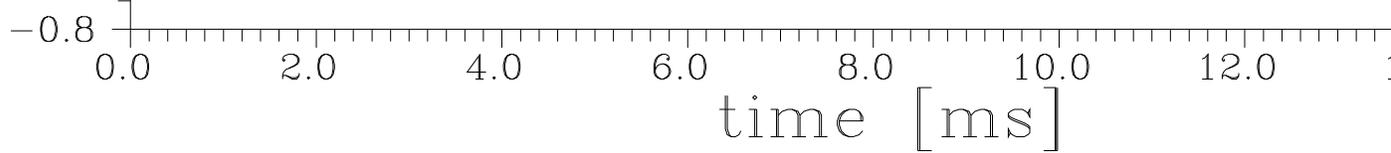
## 4. EXPERIMENT



The initial behaviour of slowly evaporating ethanol drop was analyzed and compared with the proposed numerical modeling. drops at room temperature in air of normal atmospheric pressure and observed by two CCD cameras in two directions in bright field illumination. Digitized images of drops are used to determine the drop diameter and oscillation frequency. The measured time variation of the drop diameter is used to determine the evaporation rate. An additional analysis of the drop oscillation frequency is used to determine the dependent variation of the surface tension of the drop. The variation of the surface temperature offers an unique possibility of measuring the surface temperature



**Figure 5.** shows variation of the drop equilibrium radius measured from observed decrease of the drop radius is very small (weak evaporation). The evaporation rate are underpredicted by "non-oscillating drop model". After about 10ms the evaporation rate of the drop radius decreases to the calculated values, which are of order of magnitude. The observed initial intensification of the evaporation rate can be related to the amplitudes of the drops (figure 6). The relative motion of the drop surface due to external circulation of the fluid. It modifies the heat transfer in the drop and the mass transfer between drop and gas. The second curve, "oscillating drop model" closely follows the experimental data.



**Fig.6.** *Measured amplitude of the fundamental oscillation mode for the evaporation line - approximate variation with time of the oscillation frequency.*

The measured frequency of the drop oscillation increases during analyzed time of the surface tension, meaning cooling of the drop surface. Detailed analysis needs to take into account also nonlinear effects, present at large amplitudes. The measured oscillation frequency shift is due to the variable surface temperature of ethanol.

## 5. FINAL REMARKS

Even though the initial stage of evaporation, which is drop thermal relaxation and oscillations, amounts to a small part of the total life time, the importance of this transients is obvious in many practical applications (e.g. of fuel injection in an engine) where the whole evaporation time is determined by the initial stage.

The present simple numerical model, which takes into account the heating of the drop, can properly describe its initial stage (of radius and surface temperature). It seems that its simplifications permit to predict also the influence of the drop size on the evaporation rate.

Further application of a newly developed nonlinear model of drop oscillation will allow us to verify the calculated surface evaporation rate of evaporating drops.