ABSTRACT

Condensation in the presence of non condensable gases is one of the dominating processes which determine the thermohydraulic behaviour in the primary system of a pressurized water reactor during a postulated loss of coolant accident. On this account experiments have been performed at the LAOKOON test facility at the Technische Universität München to study the effect of non condensable gases on direct contact condensation at stratified steam/water flow. The paper presents the experimental setup and the measurement techniques for the heat transfer determination, especially the linear Raman spectroscopy. This laser measurement technique allows the simultaneous investigation of concentration profiles in the vapour phase and water temperatures in the liquid phase. Furthermore the fog density in the vapour phase can be estimated, if homogenous condensation occurs in the boundary layer. The results of experiments with different system parameters are presented and the possibilities and difficulties of the linear Raman spectroscopy will both be discussed.
1. INTRODUCTION

The emergency core cooling water (ECC) accumulators in a pressurized water reactor are normally pressurized with nitrogen. Therefore the water is saturated with the nitrogen. In case of a loss of coolant accident the injection of the ECC-water releases the nitrogen as a result of the increasing temperature and the decreasing pressure. A high concentration of nitrogen is brought into the system, especially if ECC-water accumulators are emptied. The non condensable gas affects adversely the heat transfer between the vapour and the liquid phase, that ail an unmeant increase of pressure in the primary system. Furthermore only a little heating of the ECC-water by condensation of steam raises the possibility of thermal stresses in the reactor pressure vessel structure. Therefore it is important to study the condensation of water vapour at stratified steam/water flow and the temperature rise of the cooling water in presence of non condensable gases to take this effect into account.

During partial condensation non condensable gases will reduce the heat transfer rate, especially at low steam velocities, because the non condensable gas accumulates at the phase interface. In this case, measured concentration profiles in the vapour phase can be used to calculate the heat transfer coefficient by means of film theory at high mass transfer rates [1], [2]. Otherwise at high steam velocities the water temperature profile can be determined to calculate the heat transfer with energy and mass balances.

The optical measurement of the concentrations outlined in this paper bases on the linear or spontaneous Raman effect. The signal intensities obtained by Linear Raman Scattering (LRS) are rather weak. The main advantage of the LRS lies in a less complicated setup and simple evaluation of the measured signals but the intensities are much smaller compared to other non-linear methods like the Coherent Anti-Stokes Raman Scattering (CARS). An overview of possible applications for the Raman effect is given in [3].

The Raman effect is based on an inelastic scattering process. Each component of a gaseous mixture causes scattered light at wavelengths that are specific for the scattering molecule. In this paper only Raman signals caused by the vibrational $v_1$-stretching modes of $\text{N}_2$ and $\text{H}_2\text{O}$ molecules using an argon ion laser in 488 nm mode were examined. The vibrational lines of the nitrogen molecules appear at 550.6 nm and the water molecules in the vaporous phase cause a Raman line at 593.8 nm.

At higher steam velocities it is not possible to measure a concentration profile with the existing optical setup, because the boundary is very thin. In this case it is necessary to determine the heat transfer coefficients in a different way. The most common method for measuring heat transfer coefficients is to estimate the heat flux by energy and mass balances, for example by measuring the heating of a water layer. This method only works with good precision at high heat transfer rates, when a large increase of the temperature with a sufficient local resolution is obtained.

The common way to get the local temperature profile is to use micro thermocouples. They may cause two problems: the water layer is disturbed by the thermocouples and it is difficult to get the temperature profile at the interface with the necessary local resolution. In the presence of non condensable gases the heat transfer and the heating of the water is very low even at high steam velocities. Therefore it would be advantageous to get a high resolution image of the temperature profile within the boundary layer. This is also possible with Linear Raman Scattering.

In the liquid phase the water molecule will not cause a single Raman peak like in the vapour phase, because the O-H bonds are affected by the hydrogen bonds to other molecules. The number of established hydrogen bonds depends on the temperature of the water. For that reason it is possible to get the water temperature out of the shape of the Raman spectrum of liquid water.

In the experiments presented in this paper the water temperature profile was measured both with thermocouples and with Linear Raman Scattering simultaneous to the measurement of the concentration. This measurement technique is described in detail in [4], [9].

In addition the optical measurement has another advantage. In many experiments with non condensable gas fog occurs above the phase interface by homogeneous condensation. The droplets of the fog produce a liquid water Raman signal in the vapour phase and therefore it is possible to estimate the fog density using the intensity of the water signal.

2. THEORY

2.1 Film Theory of partial condensation

The local overall heat transfer coefficient is defined by the following equation:

$$\alpha = \frac{q}{T_v - T_i}, \quad (1)$$
\( \dot{q} \) represents the heat flux including diffusive heat transfer and the latent heat transported with the vapour:

\[
\dot{q} = \alpha_i (T_i - T) = \dot{m}_v \left[ (h_v - h_i) + c_{p,v} \cdot (T_v - T_i) \right] \tag{2}
\]

To determine the overall heat transfer coefficient defined in Equation (1) it is necessary to know the interface temperature \( T_i \) and if the heat transfer coefficient at the water layer \( \alpha_l \) is unknown the condensation rate \( \dot{m}_v \).

Based on conservation equation

\[
\frac{\partial x_v}{\partial t} + v \frac{\partial x_v}{\partial y} = D \frac{\partial^2 x_v}{\partial y^2} \tag{3}
\]

it is possible with the assumption of film theory to get an equation for the concentration and the temperature profile in the vapour phase [5]:

\[
\frac{x_N_i(y) - x_{N_{v}}}{x_{N_i} - x_{N_{v}}} = e^{-\frac{E_C}{RT}} = e^{-\frac{E_C}{R T_i}} \tag{4}
\]

If the concentration profiles are known, for example by optical measurement, the condensation rate \( \dot{m}_v \) can be calculated. If thermal equilibrium is assumed it is also possible to determine the interface temperature \( T_0 \).

### 2.2 Raman Spectra of the gaseous phase

It can be seen in the Raman spectra of Figure 1, that nitrogen and water vapour causes single Raman peaks, which are located at 550.6 nm (nitrogen) and 593.8 nm (water vapour) with an incitation laser wavelength of 488 nm as used in the presented experiments. The concentration of nitrogen can be calculated from the intensities of the gaseous phase Raman peaks as described below.

Assuming that the determined volume and the laser intensity are constant, the intensity relation of the scattered Raman signal may be written as [6]

\[
I_j = \text{const.} \cdot \frac{P_i}{\pi \cdot r^2} \cdot c_j \cdot V \left( \frac{\partial \sigma}{\partial \Omega} \right)_j = \text{const.} \cdot P_i \cdot L \cdot c_j \cdot \left( \frac{\partial \sigma}{\partial \Omega} \right)_j \tag{5}
\]

where the constant includes the geometry and optical arrangement of the experimental setup.

The relative Raman cross section is defined as

\[
S_j = \left( \frac{\partial \sigma}{\partial \Omega} \right)_j \left/ \left( \frac{\partial \sigma}{\partial \Omega} \right)_{N_2} \right. \tag{6}
\]

The molar density \( c_j \) of a component can be described by

\[
c_j = \text{const.} \cdot \frac{I_j}{I_1} \tag{7}
\]

where the constant includes the absolute Raman cross section of nitrogen and the experimental equipment. Since the molar density of the mixture is given by

\[
c = \frac{P}{RT} = \sum_j c_j \tag{8}
\]

it is possible to get the molar fraction of each component only with the knowledge of its relative Raman cross sections and the measured intensity:
\[ x_j = \frac{c_j}{c} = \sum_j \frac{I_j}{S_j} \tag{9} \]

For the determination of the nitrogen concentration in a steam/nitrogen mixture it is sufficient to have the Raman intensities of the two gases and the relative Raman cross section of steam.

\[ x_{N_2} = \frac{I_{N_2}}{I_{N_2} + \frac{I_v}{S_v}} \tag{10} \]

For accurate measurements it is necessary to get an exact value of the relative Raman cross section of water vapour in relation to the Raman cross section of nitrogen for the experimental setup. Values given in the literature vary largely. This results from the fact, that the relative Raman cross section depends not only on the laser’s wave number, but also on the angle of incidence of the scattered light and the polarization ratio [6]. For the presented experiments the relative Raman cross section has been calculated by a method described in [4]. It is a Gaussian least square algorithm, which uses measured intensities in vapour/nitrogen mixtures at several concentrations. For the used optical setup with a 90° configuration, a relative Raman cross section of 2.31 ± 0.26 was obtained.

2.3 Raman Spectra of the liquid phase

In the liquid phase the O-H-stretching causes not only a single peak in the Raman spectrum like in the vapour phase, but a broadband peak between 570 to 600 nm using a laser wavelength of 488 nm (Figure 1). Walrafen [7] describes a temperature dependence of the water peak shape in the region between 560 to 600 nm. This effect can be attributed to the temperature dependent equilibrium between hydrogen-bonded and non hydrogen-bonded O-H stretching oscillators in the liquid water.

Figure 2 shows the Raman spectra of liquid water at different temperatures. After subtracting a water peak corresponding to a reference temperature the normalized difference spectra intersect at the same point (isobestic point) as shown in Figure 2. The shapes of those difference spectra are useful to process the obtained image as shown below.

\[ \ln \left( \frac{[O-H]_{\text{non bounded}}}{[O-H]_{\text{bounded}}} \right) = \frac{\Delta H^0}{R \cdot T} + \frac{\Delta S^0}{R} \tag{11} \]

The temperature dependent equilibrium between hydrogen-bond and non hydrogen-bond v₁-stretching oscillators may also be interpreted as an equilibrium between hydrogen-bonded (polymer) and non hydrogen-bonded (monomer) water molecules. The concentration ratio of the established bonds represents the equilibrium constant of the equilibrium. This constant can be expressed by the enthalpy of the hydrogen bonds ΔH⁰ and the entropy ΔS⁰ [2].
The Raman peaks of the hydrogen-bound and non hydrogen-bound $v_1$-stretching oscillators are located in the difference spectra at 577.6 nm and 589.4 nm for a laser wavelength of 488 nm. Therefore it is possible to transform Eq. (11) and calculate the temperature of the liquid water with Equation (12):

$$T = \frac{\Delta H^\circ}{\mathcal{R} \cdot \ln \left( \frac{I_{577.6 \text{nm}}}{I_{589.4 \text{nm}}} \right) - c_2}$$

(12)

A comparison between temperature profiles measured with thermocouples and the recorded Raman spectra of the liquid phase provides the coefficient $c_2$.
In many experiments there is a water signal in the gaseous phase (Figure 1), if fog occurs above the phase interface. With this signal it is possible to estimate fog densities.

### 2.3 Fog density

With the recorded Raman spectra it is in addition possible to estimate a relative fog density in the vapour phase. This can be done by comparing the intensity of the liquid water signal produced by the fog droplets with the intensities of nitrogen and vapour peaks.

$$\text{relative fog density} = \frac{\frac{I_1}{c_{N_2}} + \frac{1}{c_{\text{H}_2\text{O}}} \frac{I_3}{S_v}}{I_{\text{N}_2}}$$

(13)

These intensities of the components in the gas phase depend on their molar density, the laser power and the optical setup. To compare the relative fog density of all experiments with different system pressures it is necessary to divide the intensities by their molar densities and to make sure that the laser power and the optical setup is equal at all experiments. The value calculated with Equation (13) is only a clue for the fog proportion and not absolute, but it allows the influence of the different test parameters on the fog formation to be estimated. Furthermore the influence of fog formation on the heat transfer between steam and water can be studied.

### 3. EXPERIMENTAL SETUP

To investigate the influence of different test parameters like system pressure, steam velocity, flow direction and concentration of nitrogen test series at the LAOKOON test facility were run. This test facility is located in the power station of the Technische Universität München. The flow diagram of the steam and water supply of the test section is shown in Figure 3.
Before entering the pressure vessel the steam mass flow was measured by a vortex transducer (accuracy 5%) and the water mass flow by means of a coriolis mass flow meter (accuracy 1%). A rectangular open channel is fixed inside the pressure vessel shown in Figure 3. In order to avoid disturbing effects by the measurement instrumentation only a single measurement position with windows for the optical access and thermocouples was used. This allows the simultaneous investigation of concentration profiles with LRS and of temperature profiles with thermocouples and LRS. 12 micro thermocouples (diameter 0.5 mm) are mounted on a thin fin spaced 4 mm (in the bulk of the water flow) and 2 mm (at the interface) up to 36 mm from the channel bottom. An additional thermocouple was positioned at 44 mm to measure the steam bulk temperature. The water inlet of the channel can be shifted axially. Therefore it is possible to get temperature and concentration profiles at different locations of the water layer and to state control volumes for energy and mass balances. The test facility allows the experimental parameters to be varied over a wide range as shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>0.2-1.3 MPa</td>
</tr>
<tr>
<td>Steam velocity</td>
<td>0-5 m/s</td>
</tr>
<tr>
<td>Steam temperature</td>
<td>Saturated temperature</td>
</tr>
<tr>
<td>Nitrogen concentration</td>
<td>0-20 %</td>
</tr>
<tr>
<td>Water velocity</td>
<td>0.2-0.27 m/s with a height of 30 mm</td>
</tr>
<tr>
<td>Water Reynolds number</td>
<td>10000</td>
</tr>
<tr>
<td>Water temperature</td>
<td>17-20 °C</td>
</tr>
<tr>
<td>Flow direction</td>
<td>Co- and counter-current</td>
</tr>
</tbody>
</table>

Tab. 1: Test parameters for the experiments

For the optical setup shown in Figure 4, an Ar-Laser with an output power of 1.5 W at 488 nm is used. The laser beam enters the autoclave via several mirrors. The scattered light is focused by a 50 mm objective to the entrance slit of an imaging spectrograph with a focal length of 250 mm. An intensified CCD-camera with single photon sensitivity, 385 x 576 pixels and a pixel size of 23 x 23 µm records the images. The spectra are processed by our own software described in detail in [5]. The spectrograph disperse the scattered light to different wavelengths by using a grating with a line density of 600 lines/mm and a blaze wavelength of 500 nm. In the images outlined in this paper, the horizontal axis (576 pixel) represent different wavelengths with a resolution of 0.118 nm/pixel, the vertical axis the height of the stratified flow with a resolution of 0.158 mm/pixel. With steady state conditions 30 single images with a sampling time of 2s are averaged to improve the signal noise ratio and only this average image is stored, whereas with transient conditions all single images are stored. Figure 1 shows an average image with measured and approximated spectra at different locations.

Unfortunately the intensity of the liquid water Raman peak is distinctly higher than the intensity of the nitrogen or the water vapour. Therefore for a simultaneous measurement in both phases it is necessary to weaken the signal of the liquid phase. In our experiments we accomplished this by sticking two thin steel plates on the glass pane of the channel to create a narrow slit in front of the liquid phase.
4. EXPERIMENTAL RESULTS

Experiments with steam velocities up to 5 m/s were performed at the LAOKOON test facility. In this paper only test results with steam velocities up to 0.4 m/s are presented. The reason for this is the fact, that it is not possible to determine concentration profiles and therefore local heat transfer coefficients with the existing optical setup upon a steam velocity of 0.4 m/s, but only global heat transfer coefficients by means of energy and mass balances. Interesting phenomena of direct contact condensation with non condensable gas at stratified flow are described with the selected experiments and should underline the possibilities and difficulties of the Raman laser measurement.

4.1. Steady state conditions

Most experiments were performed with steady state conditions and co-current flow. Figure 5 shows the Raman spectra of the vapour phase at co-current flow and different steam velocities. The system pressure of these experiments was 0.7 MPa and the nitrogen concentration in the steam 0.013 kmol N2/kmol H2O vapour

![Fig. 5: Raman spectra at co-current flow with different steam velocities](image)

These pictures show clearly the dependence of the nitrogen accumulation at the boundary layer on steam velocity. Underlying a critical Reynolds number of 2300 for pipe flow, the flow of the first two spectra is weakly turbulent, but the measured concentration profile can be calculated quite accurately with Equation (6). The accuracy of the heat transfer determination increases naturally with the concentration of nitrogen in the boundary layer. It can also be seen, that the limit for determination of concentration profiles is about a Reynolds number of 12000 – 15000 at co-current flow. But it must be pointed out that the water velocity is also between 0.22–0.25 m/s so the relative velocity of the steam in relation to the water is lower at co-current flow and higher at counter-current flow. This is one reason, why in case of counter-current flow no concentration profiles can be detected. An other reason lies in the setup of the measurement duct. At co-current flow the length of the water layer can be varied from 100 mm to 790 mm, whereas at counter-current flow the way of the steam is fixed at 100 mm and this is possible too short to form a concentration profile.

Determination of concentration profiles at higher steam velocities by using an lens with a higher focal length of 105 mm and thereby increasing the local resolution of the Raman spectra failed in our experiments, because the reflections of the water layer near the phase interface are too strong to determine concentration profiles up to 1-2 mm above the interface.

Fog appears surprisingly often in the vapour phase even at high steam velocities. Experiments without water feeding have shown that there are also fog droplets in the steam when cold nitrogen is injected. This happens
because the cold nitrogen detracts heat from the saturated steam and therefore a small part of the steam condenses and causes small fog droplets in the steam. If there is a cold water layer, too, the existing fog droplets are condensation nuclei and support the fog formation in the vapour phase. By heating up the nitrogen to the saturation temperature of the steam it is possible to reduce the fog formation substantially for most test parameters. As mentioned before it is also possible to estimate the fog density in the vapour phase with the recorded spectra and therefore to specify the influence of the fog on the heat transfer by making experiments with cold and hot nitrogen. Figures 6, 7 and 8 show the Raman spectra at different test parameters, each with cold and hot nitrogen.

It is obvious that the heating of nitrogen affects the fog formation largely. The heat transfer coefficient determined with Raman spectroscopy is 40% lower with a high fog density, but the heat transfer is very low in both cases. Another indication for the heat transfer is the average water temperature at the measurement point which indicates the heat transfer between the water inlet and the measurement point. With low fog density the average water temperature at the measurement point is 1.7 K higher but this value lies within accuracy of temperature determination. The concentration profiles of nitrogen in Figure 6 and other experiments indicate, that the shape of the nitrogen profiles and the absolute concentrations are dependent on the fog density.

In the experiment shown in Figure 7 the steam velocity is slightly higher whereas the nitrogen concentration is lower than in the previous experiment.

Fig. 6: Raman spectra with cold and hot nitrogen

Fig. 7: Raman spectra with cold and hot nitrogen

It can be observed, that the fog density with cold nitrogen is also low and the heating of nitrogen has no influence on the fog formation. The average water temperature difference at the measuring position is only 0.1 K too.
The thickness of the boundary layer. With the concentration profiles it is not only possible to determine heat transfer coefficients but also the analyise many different test runs to have the possibility of establishing the criteria for fog formation. steam velocity, nitrogen concentration, nitrogen temperature and their combination. Therefore it is necessary to All experiments show that fog formation and its influence on the heat transfer depends on many parameters like vapour phase in contrast to experiments without nitrogen. Therefore the nitrogen must obstruct the mass transfer formation of condensation nuclei by the cold nitrogen explained above, therefore the fog density is distinctly weaker by heating up the nitrogen. The measured average water temperature difference of 1.2 K signifies a small influence of fog formation on the heat transfer but lies also within the error limits. The experiments with hot nitrogen and high steam velocities show also, that there is still fog formation in the vapour phase in contrast to experiments without nitrogen. Therefore the nitrogen must obstruct the mass transfer to the boundary layer.

All experiments show that fog formation and its influence on the heat transfer depends on many parameters like steam velocity, nitrogen concentration, nitrogen temperature and their combination. Therefore it is necessary to analyse many different test runs to have the possibility of establishing the criteria for fog formation.

With the concentration profiles it is not only possible to determine heat transfer coefficients but also the thickness of the boundary layer.

\[ \alpha = 648 \text{ W/m}^2\text{K} \pm 214\% \]
\[ \text{fog density relative} = 42.4 \]

\[ \alpha = 1132 \text{ W/m}^2\text{K} \pm 126\% \]
\[ \text{fog density relative} = 4.6 \]

Figure 8 shows Raman spectra of an experiment with higher steam velocity and nitrogen concentrations than the two experiments before. It must be pointed out, that the signal intensity of fog, nitrogen and water vapour are distinctly lower with a high fog density than a with low fog density. This results from the weakening of the scattered light by the fog droplets. In spite of the relatively high steam velocity, the cold nitrogen causes a large fog formation above the water layer, though the accumulation of nitrogen in the boundary layer is not yet measurable. This can be observed up to steam velocities of 5 m/s. The reason for this phenomena is the formation of condensation nuclei by the cold nitrogen explained above, therefore the fog density is distinctly weaker by heating up the nitrogen. The measured average water temperature difference of 1.2 K signifies a small influence of fog formation on the heat transfer but lies also within the error limits. The experiments with hot nitrogen and high steam velocities show also, that there is still fog formation in the vapour phase in contrast to experiments without nitrogen. Therefore the nitrogen must obstruct the mass transfer to the boundary layer.

All experiments show that fog formation and its influence on the heat transfer depends on many parameters like steam velocity, nitrogen concentration, nitrogen temperature and their combination. Therefore it is necessary to analyse many different test runs to have the possibility of establishing the criteria for fog formation.

With the concentration profiles it is not only possible to determine heat transfer coefficients but also the thickness of the boundary layer.

\[ 0.7 \text{ Mpa, } v_s = 0.13 \text{ m/s, } R_s = 2490, \text{ co-current flow, } 0.022 \text{ kmol N}_2/\text{kmol steam} \]

Fig. 8: Raman spectra with cold and hot nitrogen

Fig. 9: Dependence of boundary layer thickness and heat transfer coefficients from the entry distance
Figure 9 shows the development of boundary thickness at different locations above the water layer measured by linear Raman spectroscopy. Inlet effects above the water layer that behave like a flow pattern near the leading edge of a flat plate can clearly be seen.

4.2 Transient conditions

The laser measurement technique also allows transient flows to be investigated by saving all single images as described in chapter 3. Surely the time length of the single images must correlate with the time length of the studied transient phenomena. In the experiments described the flow changes are short enough for a single image time length of 2 seconds.

Figure 10 shows Raman spectra of a co-current and counter-current flow with stagnant steam at different times. In these experiments the outlet valve was closed, therefore only the steam mass flow that condenses on the water layer flows into the test vessel by natural convection. The system pressure was constant at 0.7 Mpa. A constant cold nitrogen mass flow of 0.4 kg/h was fed in at the time 0 seconds. After 180 seconds the nitrogen injection was stopped.

There are significant phenomena appearing in these experiments. First the process of nitrogen accumulation in the boundary layer and therefore the decreasing of the heat transfer is faster at co-current flow than at counter-current flow. After 180 seconds the nitrogen concentration above the water layer is almost the same in both steam flow directions and nearly no steam condenses, so the water stays cold. It is remarkable that stopping the nitrogen feeding has different influence on the nitrogen concentration and the heat transfer at the two flow regimes. In the case of counter-current flow, the nitrogen disappears immediately after stopping the injection and the heat transfer increases to the value before the nitrogen feeding. Since the nitrogen cannot leave the system it...
must accumulate somewhere in the system. At co-current flow almost no changes of the nitrogen concentration can be observed even after a long time and the heat transfer stays low too. An explanation for the different behaviour of counter-current and co-current flow with natural convection may be the higher turbulence and interaction in the vapour phase at counter-current flow, but further analytical considerations of the experiments are necessary for a better understanding of the physical processes.

4.3. Water temperature

Figure 11 shows the comparison of a water temperature profile from the steady state experiments measured with thermocouples and the corresponding water temperatures calculated from the linear Raman spectra.

It can be noticed, that the laser-measured water temperature coincides very good with the thermocouple measurement up to about 5 mm below the phase interface. In this small region the calculated temperature stays constant, whereas the temperature of the thermocouples increases rapidly to the interface temperature as expected. But for the analysis of the flow it is very important to get the temperatures near the boundary layer. The main reason for this incorrect data is the reflection of scattered laser light from lower water layers at the interface. There is also a water signal in the vapour phase, which is caused by reflections, too. But with the given setup it is difficult to avoid reflection errors. A way to improve optical determination of the water temperature could be to make some reference measurements with the optical setup to calculate the error and to implement factors in the temperature calculation software which consider the reflection error.

Another reason for temperature error is the growth of condensate droplets at the slit in front of the water layer, which diffract the scattered laser light. In our experiments we have improved the slit by making it as narrow as possible to get a homogeneous water film at the slit and to avoid diffracting condensate droplets. As a result of this improvement the growth of droplets can be reduced but cannot be totally prevented.

5. SUMMARY

The presented measurement results point out, that the linear Raman spectroscopy with the used optical setup is an adequate method to investigate direct contact condensation in the presence of non condensable gases experimentally. In our experiments with stratified flow an accurate determination of concentration profiles is possible up to a certain nitrogen concentration in the boundary layer. If there are measurable concentration profiles they can be properly calculated applying film theory and therefore mass and heat transfer can also be determined. Independent of concentration profiles, fog densities in the vapour phase can be estimated and water temperatures can be measured with the same recorded spectra. The difficulties of getting water temperatures near the interface are described.

Some of the interesting incidences at a stratified steam/water flow are shown on the basis of the Raman spectra and described phenomenologically.
6. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>m$^2$ cross section area</td>
</tr>
<tr>
<td>D</td>
<td>m$^2$/s binary diffusivity</td>
</tr>
<tr>
<td>I</td>
<td>Counts intensity</td>
</tr>
<tr>
<td>S</td>
<td>relative Raman cross section</td>
</tr>
<tr>
<td>T</td>
<td>$^\circ$C temperature</td>
</tr>
<tr>
<td>V</td>
<td>m$^3$ volume</td>
</tr>
<tr>
<td>c</td>
<td>kmol/m$^3$ molar density</td>
</tr>
<tr>
<td>$c_p$</td>
<td>kJ/kg K specific heat capacity</td>
</tr>
<tr>
<td>h</td>
<td>kJ/kg enthalpy</td>
</tr>
<tr>
<td>k</td>
<td>constant</td>
</tr>
<tr>
<td>M</td>
<td>kg/s mass flux</td>
</tr>
<tr>
<td>$\dot{m}$</td>
<td>kg/m$^2$s specific mass flux</td>
</tr>
<tr>
<td>$\dot{n}$</td>
<td>kmol/m$^2$s specific molar flux</td>
</tr>
<tr>
<td>$\dot{q}$</td>
<td>W/m$^2$ specific heat flux</td>
</tr>
<tr>
<td>$\dot{Q}$</td>
<td>W heat flux</td>
</tr>
<tr>
<td>x</td>
<td>kmol/kmol mole fraction</td>
</tr>
<tr>
<td>y</td>
<td>m coordinate</td>
</tr>
<tr>
<td>v</td>
<td>m/s velocity</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>- normalized Raman cross section</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>W/m$^2$K heat transfer coefficient</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>nm wavelength</td>
</tr>
<tr>
<td>$\nu$</td>
<td>cm$^{-1}$ wave number</td>
</tr>
<tr>
<td>$\Delta H^0$</td>
<td>kJ/kmol bonding enthalpy</td>
</tr>
<tr>
<td>$\Delta S^0$</td>
<td>kJ/kmol K bonding entropy</td>
</tr>
<tr>
<td>Indices</td>
<td></td>
</tr>
<tr>
<td>i</td>
<td>interface, initial value</td>
</tr>
<tr>
<td>v</td>
<td>water vapour</td>
</tr>
<tr>
<td>l</td>
<td>liquid</td>
</tr>
<tr>
<td>0</td>
<td>inlet</td>
</tr>
<tr>
<td>1</td>
<td>outlet</td>
</tr>
<tr>
<td>c</td>
<td>condensation</td>
</tr>
</tbody>
</table>

Constants

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Re$</td>
<td>8,31441 kJ/kmol K gas constant</td>
</tr>
</tbody>
</table>

7. REFERENCES

2. G. Ackermann, Applied the film theory to heat transfer in the presence of rapid mass transfer, VDI-Forschungsheft, 382, 1-16 1937.