



# Quantification of re-evaporated mass from loaded fibre-mist eliminators†

Burkhard Riss\*<sup>ab</sup> Ewald Wahlmüller<sup>a</sup> and Wilhelm Höflinger<sup>b</sup>

<sup>a</sup>PROFACTOR GmbH, Wehrgrabengasse 1–5, A-4400 Steyr, Austria. E-mail: briss@pr-steyr.ac.at

<sup>b</sup>Institute for Chemical Engineering, Fuel and Environmental Technology, Vienna University of Technology, Getreidemarkt 9/159; A-1060 Wien, Austria. E-mail: whoeflin@fbch.tuwien.ac.at

Received 7th April 1999, Accepted 21st June 1999

Airborne lubricant emissions are a serious health hazard for employees in the metal working industry. The basic components of lubricants are oils and additives for adapting the properties to achieve the process demands. The oils used in lubricants are either mineral, synthetic or of biological origin. The lubricants are used as water-emulsions and also as straight oils. Extreme process conditions cause considerable amounts of aerosol and vapour emissions of lubricants into the working environment. Fibre filters are used in industrial demisters for pollution control and also for sampling purposes. Re-evaporation of separated lubricants from loaded fibre filters causes increased vapour emissions. Quantification of lubricant vapour emission was the subject of this research. An apparatus and an appropriate procedure for measuring the dynamic behaviour of evaporative losses from fibre filters were developed. The test piece of a loaded fibre filter was fixed in a sampling probe according to VDI 2066. The vapour concentration of organic compounds in downstream air was measured in real-time by using a photo-ionisation detector (PID). The PID was checked by sampling the vapour on an oleophilic adsorbent resin, solvent extraction and quantitative IR analysis and also gravimetrically. The two basic processes of filtering volatile aerosols are, on the one hand, collecting droplets on the fibres and, on the other hand, the evaporation of collected liquid. These two processes had to be separated in order to measure the increase of the vapour concentration caused by the tested fibre filter. The experiments were carried out using pure dodecane and hexadecane in order to avoid difficulties due to the unknown chemical composition of lubricant vapour. The variation of the air flow and the initial liquid mass on the filter covered the relevant range for industrial fibre demisters and for sampling methods based on collecting aerosols on fibre filters. It was found that the downstream air was saturated with lubricant vapour for a wide range of filter loads and filtration velocities. From the results obtained it can be concluded that loaded industrial filter systems emit air with saturation vapour concentration throughout their operation. Hence, vapour emissions can be estimated easily if the saturation vapour pressure and the mean relative molecular mass are known. Moreover, results obtained from measurements of filters with low loads confirm that the phase transition from liquid to vapour is influenced by the identified process parameters. This is relevant for measurement methods using fibre filters for sampling volatile aerosols. A semi-empirical model to estimate the evaporative losses for low loadings is proposed. However, further research is necessary to determine the full range of parameters that are relevant for evaporative losses from filters loaded with low masses of aerosols.

## Introduction

Extreme process conditions cause airborne emissions of metal working fluids (MWFs) at metal machining sites. Firstly, peripheral speeds of workpieces and cutting tools tear parts of the MWFs into aerosols and fine droplets. Secondly, energy dissipation at cutting processes and hot surfaces occurring at thermal treatment applications cause considerable amounts of evaporated MWFs.<sup>1</sup>

MWFs are applied either as oil-in-water emulsions or as straight oils. The basic ingredients of the lubricants are mineral or synthetic oils and hydrocarbons of biological origin. Additives adjust the properties (e.g. VT-index, corrosion, inhibiting the growth of micro-organisms) of the basic components to the specific process demands.<sup>2</sup> In spite of the low vapour pressure of MWF components ('semi-volatility'), considerable amounts of vapour phase arise at ambient conditions.

Exposure to airborne MWF emissions is known to be a serious health hazard for employees.<sup>1</sup> The current assessment

of occupational health risks regarding aerosols and vapour is still under discussion.<sup>1,3,4</sup> The assessment of occupational health risks caused by airborne MWF emissions is either based on the sum of aerosols and vapour (German approach:  $10 \text{ mg m}^{-3}$ )<sup>1</sup> or based on aerosols solely (Belgium, Finland and UK:  $5 \text{ mg m}^{-3}$ ; Sweden:  $3 \text{ mg m}^{-3}$ ). In contrast, the Austrian limit values at the workplace are  $1 \text{ mg m}^{-3}$  for aerosols and  $20 \text{ mg m}^{-3}$  for the sum of aerosols and vapour.<sup>4</sup>

A wide range of facilities such as electrostatic filters, sinter plate element filters and centrifugal force filters are available to control airborne lubricant emissions at metal working sites. Filter demisters are preferred frequently due to their high process reliability. The fact that loaded fibre mist collectors themselves can be a source of MWF vapour emissions was the subject of a recent investigation.<sup>5</sup>

Sampling lubricant aerosols on fine glass-fibre filters for measurement purposes is common practice,<sup>6</sup> although evaporative losses of collected aerosols during sampling may occur due to the volatility of the MWFs. This results in systematic underestimation of the aerosol phase. Recent measurements performed with different sampling rates and equal sampling duration prove this assumption.<sup>7</sup>

†Presented at AIRMON '99, Geilo, Norway, February 10–14, 1999.

Based on the results published in ref. 5 and 7, the goals of this work are the identification and quantification of the most important parameters for evaporative losses from fibre filters used for separation of liquid aerosol emissions. Therefore, an appropriate experimental set-up and a procedure to measure the dynamic behaviour of the evaporation process have to be developed. Losses of retained aerosols from fibre filters should be quantified. The variation of the selected parameters should include the range, which is important for industrial fibre filter systems and for sampling devices. The results obtained are discussed in detail.

## Experimental

Filtering volatile aerosols by using a fibre filter can be divided into two basic processes: collection of droplets on the filter and evaporation of collected liquid. Evaporation takes place if the vapour pressure of the collected substance is below the equilibrium (saturation vapour pressure) and liquid phase is still present. Evaporation of liquid induced by the filter takes place if the vapour load downstream is higher than that upstream [Fig. 1(a)].

The fundamental problem of measuring the concentration and ratio of liquid and vapour phase emissions by applying a measurement method based on sampling the aerosols on a fibre filter (and collecting the vapour phase *e.g.* on an adsorbent resin) is that the method itself causes a systematic error due to unknown evaporative losses of liquid from the filter during sampling time. In order to avoid the difficulties in determining the ratio of aerosol and vapour load, the two basic processes were separated within the experiments. Therefore, the test filter was drizzled manually in calm air with liquid before exposing it to the air flow.

As given in Fig. 1(a), drain-off mass flow of retained liquids may occur if the filter material becomes saturated itself. Saturation of filters implemented in a vertical position is given by the balance of gravitational forces causing the tendency of drain-off and forces caused by adherence of liquid to the fibre surface. The former forces are proportional to the retained

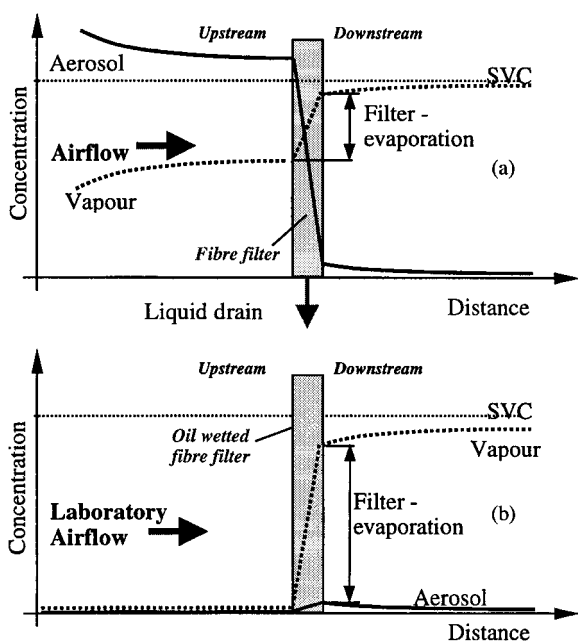


Fig. 1 Model for filtration of mixed phase emissions (schematic). (a) Loaded air flow upstream: in industrial applications, liquid drain-off is possible. (b) Situation of experiments with oil-wetted filter: vapour concentration downstream is filter induced only. SVC: saturation vapour concentration.

mass, the latter are proportional to the surface. The experiments were performed at loadings of the test piece below the saturation point of the filter material. The investigations should cover pure evaporative effects, but exclude secondary emissions of liquid particles.

Downstream aerosol loads indicated in Fig. 1(a) represent penetrated and re-emitted particles. If the equilibrium between the liquid and vapour phase downstream of the filter is not achieved, evaporation still takes place if aerosols are present. Additional problems for *in situ* detection of the dynamic behaviour of the evaporation process are caused by retention and distortion of the concentration front due to diffusion in the pipes and tubes between the filter and the measuring point. These effects may not be negligible, taking account of the low air velocities present in sampling probes or highly efficient industrial fibre filters. Penetration of aerosols was avoided by separating the filter loading process from the evaporation process as mentioned above. Re-emission of aerosols downstream was neglected. Retention within the tube and lag time of the detector were minimised by placing the suction inlet of the detector instrument as near as possible behind the test filter (approximately 5 cm). Because of the restricted suction capacity of the detector instrument with integrated pump, it was necessary to change the usual filtration process from pulling air through the filter to pushing it through by placing the pump upstream as shown in Fig. 2. Flow conditions are regarded to be equal in these two operation modes. Pressure level differs by about 1% ( $\Delta p \approx 10$  hPa) from absolute atmospheric pressure, so that changes of physical properties were regarded as negligible.

The described phenomenon which had to be considered for separating volatile aerosols on fibre filters resulted in the experimental set-up given in Fig. 2. It consists of a standardised filter holder according to VDI 2066,<sup>8</sup> wherein a test filter of 50 mm diameter was implemented. The clearance of the filter fixing was 40 mm. The variable air flow was provided by a gas sampler typically used for sampling applications (GS 312, Desaga, Germany). The sampling device recorded automatically ambient air conditions and total air volume pumped through the test filter. The pressure drop at the filter was detected by using a sensor based on a DMS bridge (Testo, Germany) and on-line recording (Testo 454, Testo).

The dynamic behaviour of the downstream vapour concentration was measured with a portable photo-ionization detector (PID 2020, Perkin-Elmer, Canada). The PID works at 10.6 eV ionization radiation; thus, only organic air pollutants are detected. The permanent air gases (argon, carbon dioxide, nitrogen, oxygen, water vapour, *etc.*) require a higher energy of ionization and are not ionised by the UV photons. The PID enables *in situ* measurements of the downstream vapour concentration.

The relevant parameters of the experiments are test filter properties, the range of air velocities penetrating the test filter, the upstream vapour load, the liquid load of the fibre filter, the

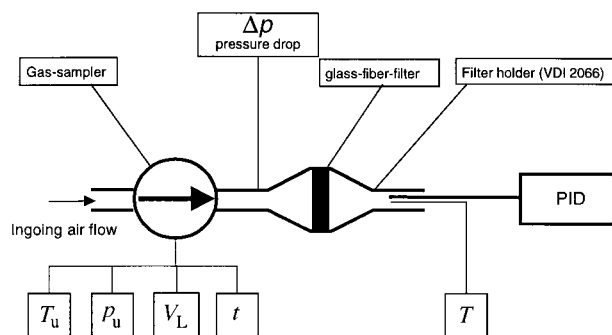


Fig. 2 Experimental arrangement (schematic).

ambient temperature, and the physical properties and chemical composition of the test fluid. Filter materials utilized for high performance filters in industrial systems applied for separating fine particles and those used for sampling are similar concerning the filter fibre diameter. The experiments were carried out using glass fibre filters (Type 13400, Sartorius, Austria; 50 mm diameter, 5–10 µm fibre diameter, ≈92% porosity), which are usually used for sampling particulate matter. Filters used in industrial applications have the same range of fibre diameter and porosity.

High performance fibre filters implemented in industrial systems are normally operated at air velocities of 0.04–0.1 m s<sup>-1</sup>. For measurement purposes liquid aerosols are sampled with filtration velocities from 0.06 (personal sampling according to BIA 3110<sup>6</sup>) to 0.5 m s<sup>-1</sup> (isokinetic sampling using GSP-PD according to VDI 2066<sup>8</sup> and BIA 3110, respectively). The experiments covered the range of filtration velocities between 0.04 and 0.2 m s<sup>-1</sup>, which resulted in flow rates of 3.5–12 l min<sup>-1</sup>.

The recommended limit value for the sum of lubricant aerosols and vapour at the workplace in Austria is 20 mg m<sup>-3</sup>. The vapour pressure of *n*-dodecane at 25 °C results in a saturation vapour concentration of 1100 mg m<sup>-3</sup> while *n*-hexadecane reaches saturation at the same temperature when an 18 mg m<sup>-3</sup> vapour load occurs. The experiments were carried out under zero vapour loads upstream of the tested filter because the maximum evaporation rates should occur [Fig. 1 (b)]. This can be regarded as a worst case scenario.

In contrast to industrial demisters where the masses loaded at fibre filters might reach the saturation point of the material for the retained liquid, the masses at filters used in sampling applications are very low. A total MWF mass of 2.1 mg would be expected at the filter if the workplace concentration of aerosols were 5 mg m<sup>-3</sup> and the total sampling air volume using BIA 3110 were 0.42 m<sup>3</sup>.<sup>6</sup> Because of difficulties in dispersing small masses on the one hand and avoiding drain-off effects at the test filter on the other hand, the range investigated covered initial masses between 6 and 200 mg (4–135 g m<sup>-2</sup>).

Temperatures of ventilated air in industrial filter systems are usually between 20 and 30 (35) °C. Sampling of MWF emissions normally takes place at ambient temperatures within 20 and 25 °C. The temperatures during the experiments were at ambient values.

The experiments were executed with two pure *n*-alkanes—dodecane (bp=216 °C; vapour pressure=16 Pa at 25 °C) and hexadecane (bp=287 °C; vapour pressure=0.21 Pa at 25 °C)—within the range of boiling-point and vapour pressure of common MWFs. For example, the vapour pressure of Macron H from Shell is about 0.5 Pa<sup>9</sup> and for CUT XU from OMV the flash-point is specified to be 180 °C.<sup>10</sup> Pure substances were chosen to avoid difficulties in detecting complex and unknown mixtures of real MWFs.

The developed procedure for carrying out the experiments was as follows: The dry test filter stored at ambient conditions was weighed. In conditions of calm air, the testing fluid was drizzled rapidly onto the filter by using a simple sprayer. Then the initial mass at the filter was determined by weighing the test-piece again. Immediately afterwards the wetted filter was placed in the filter holder and clean laboratory air was pumped through at a defined flow rate. The time-dependent downstream vapour concentration and the pressure drop at the filter and the ambient conditions were recorded automatically. The completed evaporation of the substance on the test filter was indicated by the PID recording and additionally confirmed by gravimetric methods.

The accuracy of the PID was checked by sampling the vapour on Amberlite® XAD-2 adsorbent, solvent extraction and quantitative IR analysis according to the analytical

method for measuring hazardous substances, BIA 8000 (mineral oil, vapours and aerosols).<sup>6</sup> Before starting the experimental procedure, the PID was calibrated in a saturated atmosphere of the investigated liquid by placing the suction inlet of the PID in a vapour saturated environment. Clean laboratory air for zero point adjustment was taken.

Changes in the procedure had to be made when quantitative analyses of evaporative losses of hexadecane were performed. The PID method was found not to be suitable, because the saturation concentration is very low, so that calibration of the device was not possible. For this reason the remaining hexadecane on the test piece after different exposure times to the air flow (120, 240, 360, 480, 720 min) was measured. The test filter was analysed by eluting the organic compounds with 1,1,2-trichlorotrifluoroethane (quality for IR spectroscopy, Merck, Germany) and IR spectroscopy (PE Spectrum 1000, Perkin-Elmer, Canada). With this measurement method the dynamic behaviour of concentration values cannot be investigated, but average values within intervals are feasible.

## Results

A typical time-dependent course of the PID-display and pressure drop is shown in Fig. 3. The course of the PID-display represents the current evaporation rate. After a steep rise the vapour concentration shows a high level of saturation, then a flat phase followed by a rapid decrease towards zero. The recorded pressure drop has a decreasing course and reaches a constant value at the end of the high phase of saturation. The final pressure drop of the filter is equivalent to unloaded, dry test filters.

The area below the graph of saturation ratio  $\phi$  in Fig. 3 represents the evaporated mass, which is equal to the initial mass at the end of the experiment. The initial mass placed on the filter determines the width of the high level phase.

By using the saturation ratio  $\phi$ , the temperature-corrected value of the saturated vapour pressure  $p_s$  and the ideal gas equation, the evaporated mass  $m_e$  of the test liquid can be calculated by numerical integration over the air volume  $V_L$ :

$$m_e = \int_{V_L} \rho \cdot dV_L = \int_{V_L} \frac{\phi \cdot p_s \cdot M}{R \cdot T} \cdot dV_L \quad (1)$$

where  $m_e$  [kg]=evaporated mass;  $R$  [J kmol<sup>-1</sup> K<sup>-1</sup>]=universal gas constant;  $\phi$ =saturation ratio;  $T$  [K]=temperature;  $p_s$  [Pa]=saturation vapour pressure;  $V_L$  [m<sup>3</sup>]=air volume;  $M$  [kg kmol<sup>-1</sup>]=relative molecular mass; and  $\rho$  [kg m<sup>-3</sup>]=vapour concentration downstream.

By plotting the results of the calculated evaporated mass  $m_e$  based on measured data against the air volume penetrated

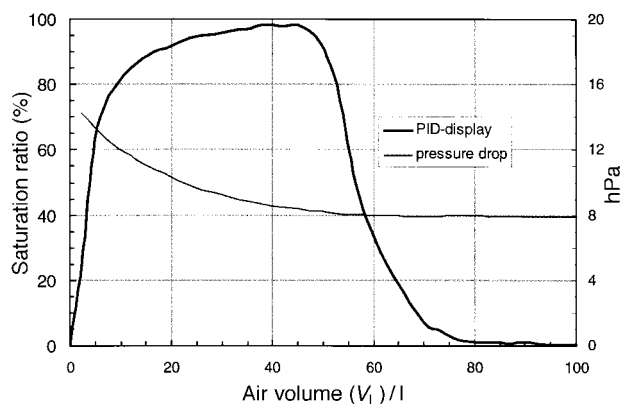


Fig. 3 Measuring data: PID instrument and pressure drop record. Test fluid: dodecane; air flow: 9.45 l min<sup>-1</sup>; initial mass 52.1 mg.

through the filter the graph given in Fig. 4 is obtained. The evaporated mass  $m_e$  shows a linear increase over a wide range.

Fig. 5 indicates the saturation ratios found within the varied range of initial masses. The parameter air flow is represented by different diameters of the bubbles. The saturation ratio  $\phi$  was calculated by using the current concentration  $\rho$  divided by the concentration of saturation  $\rho_s$ :

$$\phi = \frac{\rho}{\rho_s} = \frac{1}{\rho_s} \left. \frac{m_e}{V_L} \right|_{\text{prop.}} \quad (2)$$

For hexadecane, *in situ* measurement was not applicable. Therefore, the measurement was executed by quantitative IR spectroscopy. For hexadecane, the saturation ratio is given by eqn. (3):

$$\phi[\%] = \frac{\rho}{\rho_s} \cdot 100 = \frac{m_\alpha - M_\omega}{\dot{V}_L \cdot \tau \cdot \rho_s} \cdot 100 \quad (3)$$

where  $m_\alpha$  [kg]=initial mass;  $m_\omega$  [kg]=remaining mass on filter; and  $\tau$  [s]=test duration.

Deviations of the overall evaporated mass, calculated by using PID-measurement and checked by gravimetric determination, did not exceed  $\pm 15\%$ . A comparison performed using quantitative IR spectroscopy confirmed these results.

## Discussion and conclusion

Fig. 3–5 indicate that high rates of saturation occur if loaded fibre filters are penetrated even with clean laboratory air. Over a wide range of initial masses and air flow rates, the saturation ratio shows no dependency on these parameters (Fig. 5), except for very small initial loadings (less than 10 mg) which result in a decreasing saturation rate. This indicates that

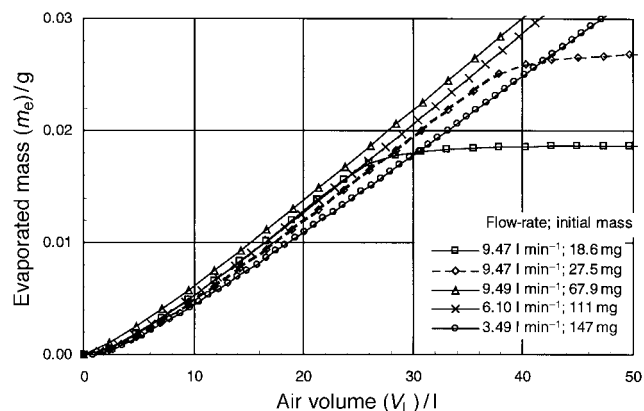


Fig. 4 Evaporative loss of dodecane from fiber filter. Data points calculated by using eqn. (1).

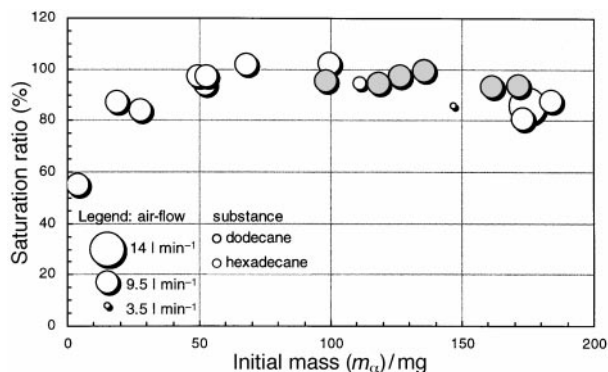


Fig. 5 Saturation ratio,  $\phi$ , depending on initial mass  $m_\alpha$  and air flow. Bubble diameters represent air flow.

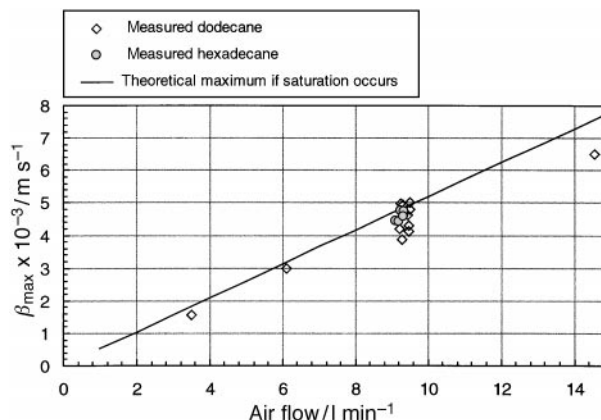


Fig. 6 Mass transfer coefficient  $\beta_{\max}$  depending on air flow.

evaporation is restricted by the provided wetted surface. Furthermore, errors due to the time lag of the measuring system probably occurred.

The experiments confirm that loaded fibre filters used for collecting semi-volatile liquids emit retained aerosols as vapour if they are penetrated by unsaturated vapour air flow. As a result of this research, exhaust air of loaded industrial fibre filters has to be regarded as saturated with lubricant vapour. Hence, vapour emissions of industrial fibre filters can be simply estimated by calculating the equilibrium load using the saturation vapour pressure (SVP), the temperature of the ventilated air measured at the site and the mean relative molecular mass. Unfortunately, SVP and mean relative molecular mass are seldom specified in the safety data sheet. If only flash-point or boiling-point is given in the safety data sheet a reference value of saturation pressure for lubricants based on mineral oil fractions can be obtained from monographs in *e.g.* ref. 11. A rough estimation of lubricant vapour production by a typical industrial fibre filter at a  $3000 \text{ m}^3 \text{ h}^{-1}$  ventilated air flow gives a value of approximately  $3.2 \text{ kg h}^{-1}$  if the vapour pressure of the lubricant is similar to that of dodecane and approximately  $55 \text{ g h}^{-1}$  if the vapour pressure is similar to that of hexadecane.<sup>15</sup>

For very small masses on the filter, which occurs *e.g.* in measurement applications based on sampling aerosols on fibre filters, the situation might be more complex. Assuming that saturation downstream of the filter does not occur when deposited masses on the fibre filter are very low (*e.g.* less than 10 mg on a filter of 50 mm diameter), a characteristic, based on the theory of convective mass transfer, is proposed below for predicting evaporative losses.

Considering the theory of convective mass transfer,<sup>12–14</sup> the actual mass-transfer coefficient  $\beta$  is defined by eqn. (4). Taking the proportional section of the of drawn lines in Fig. 4, a maximum coefficient  $\beta_{\max}$  can be determined [eqn. (5)]:

$$\beta = \frac{\dot{V}_L}{S \cdot \rho_s} \cdot \frac{dm_e}{dV_L} \quad (4)$$

$$\beta_{\max} = \frac{\dot{V}_L}{S \cdot \rho_s} \cdot \left. \frac{\Delta m_e}{\Delta V_L} \right|_{\text{prop.}} \quad (5)$$

where  $\beta[\text{m s}^{-1}]$  = mass transfer coefficient;  $\beta_{\max}[\text{m s}^{-1}]$  = maximum mass transfer coefficient;  $\rho_s[\text{kg m}^{-3}]$  = saturation concentration;  $\dot{V}_L[\text{m}^3 \text{ s}^{-1}]$  = volume flow; and  $S[\text{m}^2]$  = surface of fibres.

For hexadecane, where *in situ* values for evaporative losses were not achievable, data acquired by quantitative IR spectroscopy are used to calculate a coefficient for mass transfer

[eqn. (6)]:

$$\beta_{\max} = \frac{m_{\alpha} - m_{\omega}}{\tau \cdot S \cdot \rho_S} \quad (6)$$

For the surface  $S$  in eqns. (4)–(6), the surface of fibres calculated by eqn. (7) was used.  $S$  was regarded as a material constant and therefore uncertainties in the amount of the actual wetted surface have to be modelled by the mass transfer coefficient  $\beta$ .

$$S = S_V \cdot (1 - \varepsilon) \cdot D^2 \cdot \frac{\pi}{4} \cdot B \quad \text{with } S_V = \frac{S_{\text{fibre}}}{V_{\text{fibre}}} = \frac{4}{d} \quad (7)$$

where  $S_V$  [ $\text{m}^{-1}$ ] = specific surface;  $\varepsilon$  = porosity;  $D$  [m] = effective diameter of filter piece (clearance of filter holder);  $B$  [m] = thickness of filter;  $S_{\text{fibre}}$  [ $\text{m}^2$ ] = surface of one fibre;  $V_{\text{fibre}}$  [ $\text{m}^3$ ] = volume of one fibre; and  $d$  [m] = diameter of one fibre.

In Fig. 6,  $\beta_{\max}$  for all the experimental results (near and below saturation) was calculated. In addition, the theoretical value for saturation is plotted. Fig. 6 shows that most of the calculated values for  $\beta_{\max}$  are near the theoretical maximum value. The points at an air flow of  $9.51 \text{ min}^{-1}$ , which are significantly below the saturation value, were obtained from measurements where the initial mass was at the lower end of the range. Further investigations are needed to ascertain whether evaporative losses of measurement applications with low loadings (<5 mg) are significant and if  $\beta_{\max}$  is a proper characteristic in these cases.

Further investigation is necessary to determine the dependency of evaporation on fibre diameter, ingoing droplet size distribution and the change of composition during evaporation of a complex cooling lubricant.

## References

- 1 HVBG, Berufsgenossenschaftliches Institut f. Arbeitssicherheit, BIA Report 7/96, *Kühlschmierstoffe*, St. Augustin, 1996.
- 2 T. Mang, *Die Schmierung in der Metallbearbeitung*, Vogl, Würzburg, 1983.
- 3 US Department of Health and Human Services (NIOSH), *Occupational Exposure to Metalworking Fluids—Criteria for a Recommended Standard*, NIOSH, Cincinnati, OH, Publication No. 98–102, 1998.
- 4 AUVA Merkblatt M 368–1097, *Kühlschmierstoffe*, Unfallverhütungsdienst der Allgemeinen Unfallversicherungsanstalt, Vienna, 1997.
- 5 D. Leith, F. A. Leith and M. G. Boundy, *Am. Ind. Hyg. Assoc. J.*, 1996, **57**, 1137.
- 6 HVBG, *Messung von Gefahrstoffen—BIA Arbeitsmappe*, Erich Schmidt Verlag, Bielefeld, 12. Lfg. IV/94, 1994.
- 7 D. Breuer, unpublished work.
- 8 Verein Deutscher Ingenieure, VDI-Richtlinien 2066 Blatt 2, Düsseldorf, 1993.
- 9 Shell Austria, Sicherheitsdatenblatt gemäß 93/112/EG zu Material 56930, 1996.
- 10 OMV, Sicherheitsdatenblatt Pd. Nr. 177.615, 1996.
- 11 *Arbeitsmappe für Mineralölingenieure*, Deutscher Ingenieur Verlag, Düsseldorf.
- 12 H. D. Gahr and K. Stephan, *Wärme- und Stoffübertragung*, Springer-Verlag, Berlin, 1994, p. 340.
- 13 H. Brauer, *Stoffaustausch Einschließlich Chemischer Reaktionen*, Sauerländer, Aarau, 1971, pp. 110 and 333.
- 14 G. Hanel, *Einführung in die Konvektive Wärme- und Stoffübertragung*, Verlag Technik, Berlin, p. 148.
- 15 B. Riss, Diplomarbeit, TU Wien, 1999.

Paper 9/02767J