Pergamon

Int. J. Heat Mass Transfer. Vol. 38, No. 6, pp. 1105–1110, 1995
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0017–9310/95 $9.50+0.00

0017–9310(94)00229–0

Measurement of the thermal conductivity of fluids with low viscosity under reduced gravity conditions using the transient hot-wire technique

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(*Received* 30 *March* 1994 *and in final form* 17 *June* 1994)

Abstract—Under normal gravitational conditions the measurement of the thermal conductivity λ is often strongly influenced by thermal convection. Heat transfer by convection superposes the heat transfer due to thermal conduction. Systems in which the gravity effects are compensated, e.g. under microgravity conditions, offer decisive advantages because natural convection is strongly suppressed. In this paper an apparatus is described enabling accurate measurements in fluids with low viscosity without any gravitational influence. Comparative measurements carried out in the 'Drop Tower Bremen' using isopropanol, ethanol and cyclohexane are presented and compared to data available in the literature.

INTRODUCTION

The precise determination of thermal conductivity of fluids is centrally important for the modelling of molecular transport processes and for the optimization of terrestrial and orbital processes.

Molecular transport mechanisms in pure media depend strongly on temperature and less on pressure. In the case of mixtures the concentration is also important [1–3]. For ideal gases and solid bodies there are well-founded theories to explain the heat conduction mechanism. In the presence of a liquid phase the modelling of heat transport becomes more difficult because of complex molecular interactions, so that a satisfying theory does not exist. The model development and testing is complicated because the existing data are not sufficiently precise. For example, λ-values obtained by different experimenters show differences of up to 85%. A main source of error is the influence of gravity.

The importance of precise data on thermal conductivity λ for the optimization of physico-chemical processes is directly evident. Firstly, a large number of processes exists, in which thermal energy is exchanged as a result of temperature differences in fluids at rest, and for which precise data are required for design and optimization. However, a study of the relevant literature shows that such data for the common industrial media are still relatively uncertain. Heat conduction data for mixtures have only been measured in special cases, although these are of prime practical importance. The calculation equations given in the literature [4] are only approximate (errors of 50% are common).

For the determination of the heat conductivity λ of fluid media in a terrestrial laboratory, the gravitation vector leads to restrictions in the measurement technique. The temperature gradient which is necessary for the determination causes interference through convective currents (natural convection or density stream). A large part of instrument development has been concentrated on reducing this interference.

The experiment presented here allows the accurate measurement of heat conductivity of low-viscosity fluids by means of the transient hot-wire technique (time-dependent temperature field) under microgravity, without the interference of thermal convection. The non-stationary hot-wire method depends on the measurement of transient temperatures, thereby requiring much shorter measurement times as compared with a stationary method like the two-plate method. Also advantageous is the relatively low apparatus requirement for the reduction of error parameters, such as the undesired heat transfer on the boundaries of the measurement cell. Because of the short experiment times, one does not require an auxiliary heater to compensate for possible changes in enthalpy.

However, one major problem in measuring the thermal conductivity λ in fluids with low viscosity is the early onset of convection in the presence of gravity. Depending on the viscosity of the fluid, e.g. on the Prandtl number, which is typically of the order of 1–

NOMENCLATURE

a	thermal diffusivity
l	length
Ei	exponential integral function
Fo	Fourier number, $4at/r^2$
$\dot{q}$	heat flow per unit length
R	ohmic resistance
r	radius of the hot wire
t	time
U	voltage.

Greek symbols

γ	Euler's constant, $\gamma = 0.5772$
ε	small difference
ϑ	temperature of the wire
λ	thermal conductivity.

Subscripts

fit	index approximation
meas	index measurement.

100 for the fluids in question, the time between starting measurement and starting convection may be less than 0.5 s. Unfortunately, the short remaining measuring time causes errors in measurement which are larger than disturbances caused by the apparatus.

PRINCIPLES OF THE HOT-WIRE TECHNIQUE

The hot-wire technique makes use of a thin hot wire, which is heated with a constant current producing a heat flow per unit length $\dot{q}$ and an increase of the hot-wire temperature. A small part of the supplied heating current is used to heat the wire; the major part is used to heat the surrounding medium via thermal conduction. The variation of wire and medium temperature with time depends directly on the heat conductivity of the medium and the supplied thermal energy.

The temperature rise of the hot wire is given by the non-stationary Fourier differential equation [equation (1)], assuming a line-shaped isotropic heat source with cylinder geometry:

$$\frac{\partial \vartheta}{\partial t} = a\frac{\partial^2 \vartheta}{\partial r^2} + \frac{\dot{q}}{\rho c_p}. \tag{1}$$

Assuming a constant heating power and material constants not depending on temperature, equation (1) can be solved exactly:

$$\vartheta(r,t) = -\frac{\dot{q}}{4\pi\lambda} Ei\left(-\frac{r^2}{4at}\right) \tag{2}$$

where Ei is the exponential integral function:

$$-Ei(-x) = \int_x^\infty \frac{e^{-u}}{u}\,du. \tag{3}$$

To characterize the temperature rise of the hot wire the Fourier number Fo is introduced:

$$Fo = \frac{4at}{r^2}.$$

In the case of Fourier numbers larger than 50 the temperature rise of the hot wire is described by the logarithmic approximation equation (4) [6]:

$$\vartheta(r,t) = \frac{\dot{q}}{4\pi\lambda}(\ln Fo(r,t) - \gamma) \tag{4}$$

where γ is the Euler constant ($\gamma = 0.5772$). Using the slope of this function the heat conductivity, λ is calculated. The temperature change ($d\vartheta$) of the hot wire is measured as a change in its ohmic resistance.

EXPERIMENTAL SETUP

Figure 1 shows schemetically the setup of the used measurement cell using the hot-wire technique and the necessary electronic equipment. The experimental setup for the measurement of the thermal conductivity consists of a cylindrical measurement cell in which a platinum hot wire ($\varnothing = 0.025$ mm, $l = 100$ mm) is mounted horizontally. The temperature of the measurement cell is controlled by a peltierelement-based thermostat within a range of 0–60°C with an accuracy of ±0.1°C.

The hot-wire temperature is measured using a microprocessor-controlled bridge assembly based on a constant current source to provide a constant heat flow per unit length ($\dot{q}$) in the hot wire, and a reference voltage source represented by a digital to analogue converter (Fig. 2). The voltage along the hot wire is compared to the reference voltage, which is fixed at a calculated value, taking into account the fluid temperature at the beginning of the measurement, the heating current and the calibration parameters of the hot wire.

The design of the measurement electronics offers most flexibility in this application, because the hot wire can not only be used as a heat source and temperature sensor for measuring the thermal conductivity; it serves also as a heater control sensor to register the actual temperature of the fluid in the measurement cell.

A special microprocessor unit adapted to the requirements of drop tower applications enables an automatic operation of the experimental setup as a stand-alone system. A three-axis accelerometer detects the release of the drop capsule, which triggers the beginning of the period of measurement. Residual

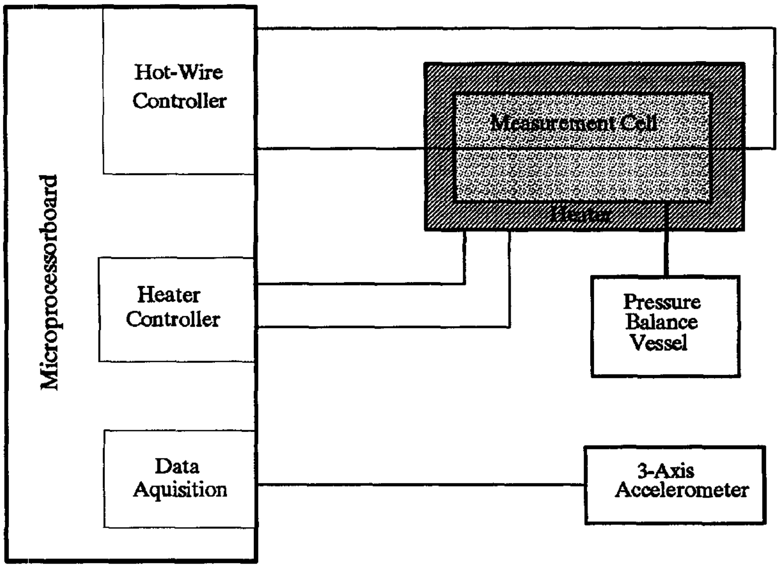

Fig. 1. Scheme of the experimental setup using the hot-wire technique.

accelerations during the drop period are recorded and stored to monitor the quality of microgravity.

RESULTS

The temperature rise of the hot wire is given by the logarithmic approximation, equation (4), which is only valid in the case of Fourier numbers larger than 50.

The slope of this approximation is used to determine the thermal conductivity:

$$\lambda = \frac{\dot{q}}{4\pi} \cdot \frac{\ln(Fo(t_2)) - \ln(Fo(t_1))}{\vartheta(r, t_2) - \vartheta(r, t_1)}. \qquad (5)$$

Figure 3 shows a typical temperature rise of the hot wire, obtained during measurements in isopropanol under 1 *g* conditions using the experimental setup described above. The measured hot-wire temperature (solid line) and the calculated temperature (dashed line), using the logarithmic approximation, are plotted vs the Fourier number in logarithmic scale. For $Fo \geqslant 150$ (left arrow), the measured temperature rise is in good agreement with the calculated hot-wire temperature. The early onset of an additional convective heat flow for $Fo \geqslant 3000$ (right arrow) leads to a higher cooling rate of the hot wire than the predicted one if the only effect is pure thermal conduction. The logarithmic approximation is not valid furthermore in the case of $Fo \geqslant 3000$.

To calculate the thermal conductivity using the measured hot-wire temperature, as shown in Fig. 3, first the Fourier number range for an accurate approximation has to be defined. The lower limit of the Fourier number range is determined by the physical properties of the used platinum hot wire, whereas the smooth onset of convection complicates the defi-

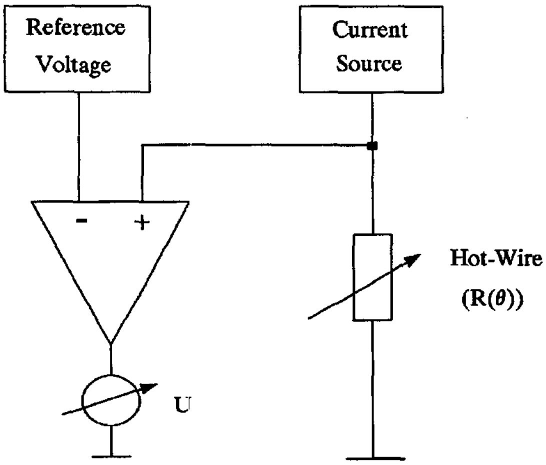

Fig. 2. Scheme of the measurement bridge used.

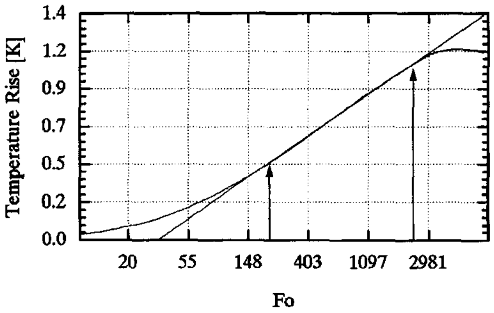

Fig. 3. Temperature rise recorded unter 1 *g* conditions (solid line) compared to the logaritmic approximation (dashed line). The two arrows mark the upper and lower limit of the Fourier number range in which the measured temperature rise fits a logarithmic function.

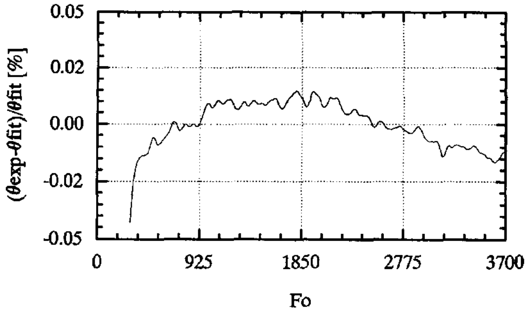

Fig. 4. Accuracy of the logarithmic approximation (1 *g* conditions).

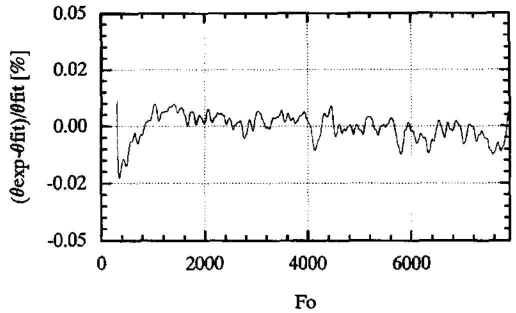

Fig. 6. Accuracy of the logarithmic approximation (microgravity conditions).

nition of the upper limit of the applicable Fourier number range. A proper criterion for the determination of a suitable Fourier number range to fit the measured data is given by equation (6):

$$\| \vartheta(t)_{\text{meas}} - \vartheta(t)_{\text{fit}} \| \leqslant \varepsilon. \qquad (6)$$

Setting the limit of the difference, ε, between measured temperature and fitted temperature to a maximum value of $\varepsilon = \pm 0.004°\text{C}$, which strongly depends on the maximum temperature resolution of the apparatus, an accuracy of the logarithmic fit of $\pm 0.02\%$ within the applicable Fourier number range is achieved, as shown in Fig. 4.

By carrying out measurements under microgravity conditions, errors due to an additional heat transfer driven by convection can easily be avoided, as depicted in Fig. 5, in which the hot-wire temperature is plotted vs the Fourier number *Fo* (logarithmic scale). The applicable Fourier number range for measurements without any convective effects is only limited by the time of flight of the drop capsule. Using the same criterion to test the quality of the logarithmic approximation as applied when gravity effects are present, the same accuracy of the fit is achieved within the whole microgravity period, thus leading to a duplication of the effective time for measurement (Fig. 6).

Many measurements of the thermal conductivity of fluids with low viscosity using the transient hot-wire technique have been reported in the literature. However, only a few measurements of molten semiconductors under microgravity conditions have been carried out by a Japanese group [3]. Measurements of the thermal conductivity of fluids with low viscosity under reduced gravity conditions are not reported. A comparison between measurements under microgravity and gravity conditions might help to improve measurement techniques under gravity conditions, thus leading to more reliable values of the thermal conductivity with a higher level of accuracy. Comparative measurements of the thermal conductivity under gravity and microgravity conditions can easily be realized in the 'Drop Tower Bremen' using the preparation period of each drop to carry out reference measurements under 1 *g* conditions with exactly the same calibration parameters as are used in microgravity.

Three different fluids have been used for comparative measurements: isopropanol, ethanol and cyclohexane. For those fluids, reference values of the thermal conductivity are available in the literature [4, 5] for comparison with the experimental data. In Fig. 7 the thermal conductivity of isopropanol obtained under microgravity (△) is plotted vs the fluid temperature. Reference data measured under 1 *g* conditions (□) and data cited in the literature (●) [4, 5] are also listed in comparison with the microgravity data. The error bars are mainly determined by a systematic error (≈ 0.5%) and the error in the deter-

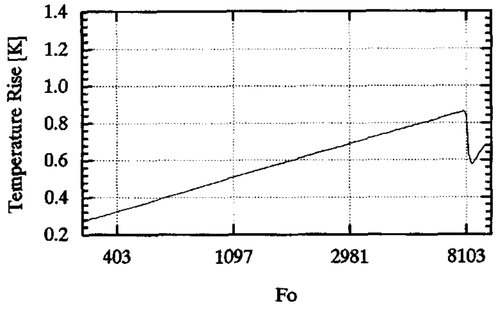

Fig. 5. Temperature rise recorded under microgravity conditions.

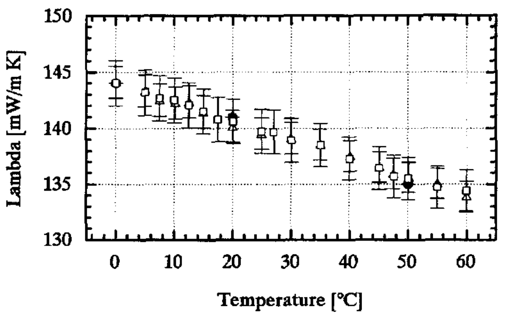

Fig. 7. Measured data of the thermal conductivity of isopropanol (□: 1 *g* conditions; △: microgravity conditions) compared to data available in the literature [4, 5] (●).

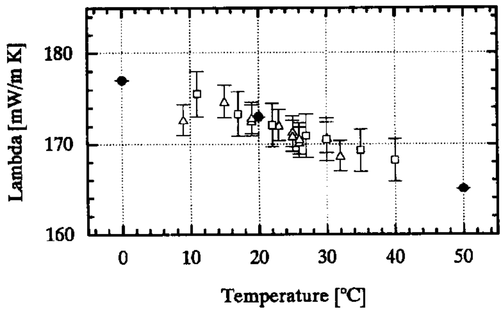

Fig. 8. Measured data of the thermal conductivity of ethanol (□ : 1 *g* conditions ; △ : microgravity conditions) compared to data available in the literature [4, 5] (●).

mination of the slope of the temperature rise. This error is estimated using the Gaussian error propagation law, taking into account the accuracy in determining the hot-wire temperature via the thermal calibration function of the hot wire (±0.06%) and the applicable time for measurement. Under 1 *g* conditions, the error bars are in the order of 1.2%, whereas the accuracy of the data under microgravity conditions is increased to 1% error. Within the error bars, the microgravity data agree very well with the reference data and those values cited in the literature. Nearly the same behaviour is detected in the case of ethanol (Fig. 8) and cyclohexane (Fig. 9).

CONCLUSIONS

The determination of the thermal conductivity of fluids with low viscosity is strongly influenced by the early onset of an additional heat transfer due to a convection-driven density flow in the fluid under test. Heat transfer based on free convection superposes the heat transfer due to pure heat conduction, thus leading to a poor level of accuracy in the evaluation of the experimentally found thermal conductivity. Hahne and Song [7] reached an accuracy in their experiments of about 1.6%, neglecting the error due to time limitation.

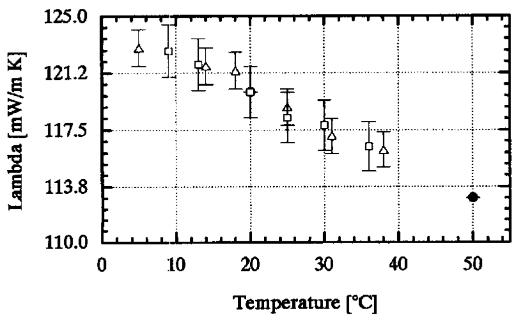

Fig. 9. Measured data of the thermal conductivity of cyclohexane (□: 1 *g* conditions; △: microgravity conditions) compared to data available in the literature [4, 5] (●).

The accuracy of the determination of the thermal conductivity is improved by using a non-stationary measurement technique, which is based on a transient temperature field in the fluid under test. In this application the transient hot-wire technique has been proved to be the most suitable method to measure the thermal conductivity. An accuracy of 1.2% was achieved by carrying out measurements of isopropanol, ethanol and cyclohexane with gravity present. The influence of an additional convective heat transfer could be detected and was eliminated, thus leading to a short applicable measurement time. A comparison of the experimentally found data to data available in the literature showed a good agreement.

By carrying out measurements of the thermal conductivity under reduced gravity conditions, disturbing convective effects are reliably eliminated. In comparative experiments the measurement time under microgravity was only limited by the time of flight of the drop capsule. The expansion of the measurement time leads to an increase in the accuracy of the experimentally determined thermal conductivity, which was found to be 1%.

The comparison of the thermal conductivity of isopropanol, ethanol and cyclohexane obtained during reference measurements when gravity is present with values measured under microgravity conditions, showed that under microgravity a much longer time is available for measurements with a higher level of accuracy. A good agreement was found between the data found experimentally under gravity conditions, as well as under microgravity conditions, with data available in the literature.

The microgravity environment has been proved to be a very good possibility for preventing any additional heat transfer caused by convection, which lowers the measurement accuracy. The accuracy of the experimentally determined values only depends on systematic errors of the apparatus and the evaluation algorithm. As long as the thermal conductivity has to be determined experimentally, the microgravity environment offers decisive advantages to increase the accuracy of this important material constant.

Acknowledgement—This work was supported by the Deutsche Agentur für Raumfahrtangelegenheiten (DARA) under grant number 50-QV 8898-1.

REFERENCES

1. H. Iglseder, H. J. Rath, J. Beeck, H. J. Königsmann and H. Oelze, BREM-Sat: a small university satellite, ESA SP-298, Frascati, Italy, Research programme of the German spacelab mission D-2, 1, Experimenters working group meeting D-2, Aachen (1989).
2. W. Jobst, Messung der Wärmeleitfähigkeit von organischen, alphatischen Flüssigkeiten und Gasen nach einem instationären Absolutverfahren, Dissertation (promotion no. 3547), ETH, Zürich (1964).
3. S. Nakamura, T. Hibiya, F. Yamamoto and T. Yokata, Measurement of the thermal conductivity of molten InSb under microgravity, *Int. J. Thermophys.* **12**(5), 783–789 (1991).

4. VDI, *VDI-Wärmeatlas* (1988).
5. Lanold-Börnstein, *Zahlenwerte und Funktionen*, Band II. Springer-Verlag, Berlin (1969).
6. H. S. Carslaw and J. C. Jäger, *Conduction of Heat in Solids* (2nd Edn). Clarendon Press, Oxford (1959).
7. E. Hahne and Y. W. Song, Messung der Wärmeleitfähigkeit von R115 bei hohen Drücken nach der Heißdraht-Methode, *Wärme- und Stoffübertragung* **24**, 79–85 (1989).