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THE AEROSYPHON: AN EXPLORATORY STUDY

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Abstract—The paper is an experimental investigation of the aerated-thermosyphon, or aerosyphon. The work combines a visual flow study with a series of heat-transfer experiments in an attempt to understand the *modus operandi* of the device and explore its unusual heat-transfer characteristics.

NOMENCLATURE

d,	orifice diameter [m];
n,	number of orifices;
$\dot{v}$,	air flow rate [m^3/s];
β,	thermal coefficient of expansion [1/°C];
ν,	momentum diffusivity [m^2/s];
κ,	thermal diffusivity [m^2/s];
k,	thermal conductivity [W/m-°C];
g,	gravitational acceleration [m/s^2];
a,	tube radius [m];
L,	tube length [m];
T,	temperature [°C];
θ,	overall temperature difference [°C];
$\dot{Q}$,	overall heat flux [W];
$\dot{W}$,	power supplied by air [W];
Nu_a,	$= \dfrac{\dot{Q}}{2\pi L_H \theta k}$, Nusselt number using tube radius;
Re_d,	$= \dfrac{\dot{v}}{\pi d n \nu}$, orifice Reynolds number;
Ra,	$= \dfrac{\beta g \theta a^3}{\nu\kappa}$, Rayleigh number of liquid.

Subscripts

H, C,	heated, cooled;
W,	tube wall;
1,	core at entry.

INTRODUCTION

IT HAS been known for many years that thermosyphon tubes provide a very effective and compact means of transferring heat. Unlike heat pipes they take advantage of a body force field to promote a vigorous internal circulation which is the source of their effectiveness. Many forms of thermosyphon tube have been devised and tested with some particular application in mind and it has been found repeatedly that those utilizing a boiling–condensation mode produce the highest heat fluxes.

In a recent project in northern Canada [1] consideration was given to the building of an ice dam using a row of long, vertical thermosyphon tubes inserted through the ice cover of a river such that the cold prevailing winds would carry away the heat being transmitted through the thermosyphons from the water. In the near-freezing water surrounding the immersed sections of the thermosyphon tubes the heat removed would be largely latent, thus implying a row of growing cylindrical ice shells which, when they eventually contacted each other, would form a continuous wall of ice. A review of suitable forms of thermosyphon revealed both merits and de-merits for each of the existing types. In the search for alternatives some thought was given to the idea of augmenting the buoyancy in a single-phase system with columns of air bubbles (Fig. 1) so that internal circulation could be substantially increased in a controlled manner. However, no data could be found for such a system and it was this absence which promoted the present study of aerated-thermosyphons. When the buoyancy forces are predominantly due to the presence of air

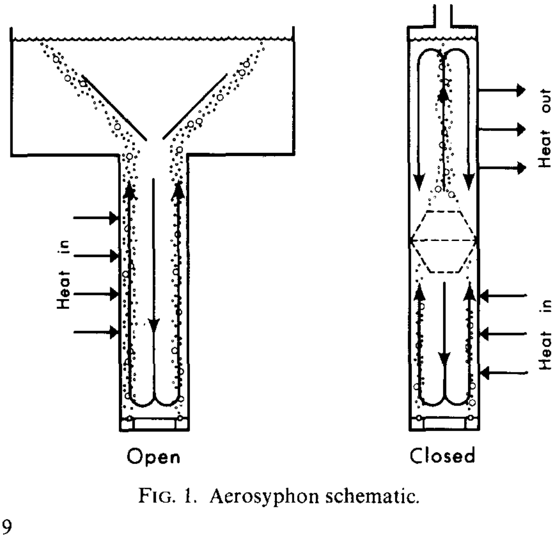

FIG. 1. Aerosyphon schematic.

bubbles an appropriate contraction of "aerated thermosyphon" is *aerosyphon* by which name the device will henceforth be described.

The first comprehensive analysis of the thermosyphon was executed by Lighthill [2] whose work was restricted to single-phase behaviour. Lighthill's work has since formed the basis of comparison for several experimental studies [3–6] of both the open and closed thermosyphons. An exploratory study of the boiling thermosyphon was reported in 1955 [7] and has recently been extended and largely reconfirmed by the work of Larkin [8] and Lee and Mital [9]. Heat transfer in aerated systems has been widely studied in other contexts but only a very small amount of work [10, 11] appears to be relevant to the behaviour of thermosyphons or aerosyphons.

The simplest way to analyse the aerosyphon is to assume that aeration produces nothing more than buoyancy augmentation. If this were true then the effective buoyancy would be increased by the density ratio; that is, the density of water (minus that of air) divided by the thermally-produced density change in the water. In cold water, it is not difficult for this ratio to exceed 10^3 so that for a turbulent "free convection" boundary layer the Nusselt number could increase by an order of magnitude. For an open aerosyphon this would correspond to Nusselt numbers as high as those recorded for the closed boiling system. However, such a prediction is simplistic and takes no account of the role of latent heat or of the lack of circulatory control in the evaporative systems. Presumably, these effects would be in opposition so that it is especially difficult to know which would dominate. Nevertheless, there is some evidence [10, 11], limited though its relevance may be, to suggest that the performance of an aerosyphon can approach that of the boiling thermosyphon.

A complete description of the thermal behaviour of the aerosyphon would include many independent variables. Written in non-dimensional form, these may be divided into three main groups:

(i) Dynamic ratios; e.g. Rayleigh number, Reynolds number
(ii) Property ratios; e.g. Prandtl number, liquid/gas properties
(iii) Geometrical ratios; e.g. tube radius/tube length, orifice radius/tube radius.

In this exploratory study, only the ratios in the first group will be treated as variables. The ratios in the second two groups will be fixed by the use of a given air–water system: this is an arbitrary but convenient choice.

APPARATUS

Heat-transfer experiments

Heat-transfer experiments were conducted on both the open and closed systems. Figure 2 shows the basic layout of the open-system apparatus. In essence, it consisted of a 7·6 cm I.D., 0·91-m long, vertical brass tube closed at the bottom end and open at the top where it was connected by a smooth, rounded entry to a cylindrical aluminum reservoir 0·4-m dia. and 0·2-m deep. During operation both the reservoir and tube were full of water.

Heat was transferred to the water through the tube wall by means of semi-cylindrical resistive heaters wrapped around the wall. The heaters, in turn, were surrounded by an air gap and thermal insulation to reduce heat leakage: electrical guard heaters on the outer surface of the insulation were used to maintain this leakage below a negligible level. The use of heater sections of 17·8-cm length, each with a separate power supply, gave some freedom of choice in the thermal boundary conditions: in fact, the experiments were

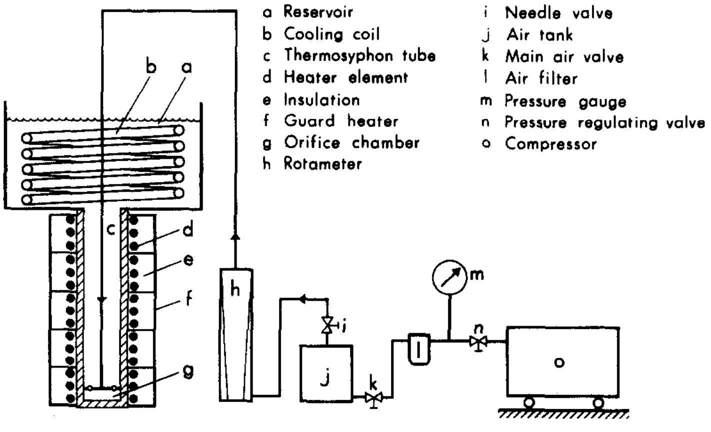

Fig. 2. Open aerosyphon apparatus.

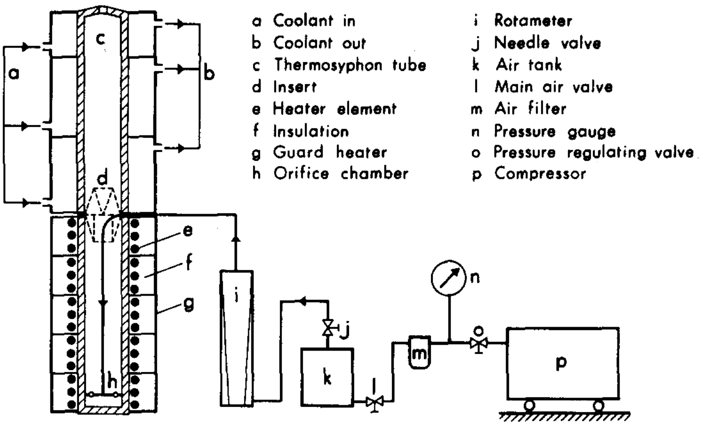

FIG. 3. Closed aerosyphon apparatus.

conducted with an isothermal tube wall. No heat was deliberately supplied to the base of the tube but an isothermal, rather than adiabatic, condition was believed to exist there too. The A.C. power supplied to the heaters was controlled through Variac transformers and measured with a Cambridge wattmeter.

In the reservoir, heat was carried away by means of a copper cooling coil through which cold water was circulated.

Temperatures were measured with copper–constantan thermocouples located at appropriate points in the tube wall and the surrounding insulation. In addition, a thermocouple probe for measuring the water temperature at the mouth of the tube was also installed. This probe was located along the tube axis and could be traversed vertically. The thermocouple leads were connected to a high-precision switching unit, the output from which was measured on a potentiometer using a null method.

Aeration was produced from a ring of orifices located on the top of a disk-shaped air chamber which fitted loosely into the bottom of the brass tube. The orifice ring consisted of a number of equally spaced holes of uniform diameter ranging from 0·813 to 1·57 mm; the ring diameter was kept at 7·4 cm. Air was supplied to the chamber along a 2-mm dia. tube running along the axis of the aerosyphon. This small-bore tube was connected to a rotameter by means of which the air flow rate was measured. The rotameter, in turn, was connected to an air surge tank which was supplied with compressed air by a small compressor. A needle valve with a micrometer adjustment was used to give fine control of the air flow rate.

A similar layout for the closed* system is shown in Fig. 3. The same air-supply and aeration system were used with a minor change in the access path of the small-bore tube. The heated, lower section of the aerosyphon also remained unchanged.

The cooled, upper section consisted of an identical brass tube placed in an inverted position on top of the lower tube and separated from it by a small spacing ring of insulating material. The "closed" cavity thus formed was filled with water which was allowed to overflow at the top during aeration. Cooling of the upper tube was accomplished with water jackets which, like the heaters, were installed in sections. The limited freedom of choice in the thermal boundary conditions was again exercised in favour of an isothermal† wall. No attempt was made to control thermal conditions on the top end of the tube. The closed system, like the open system, was always open to the atmosphere.

Some experiments on the closed system were conducted with an insert located in the centre of the system, as indicated by the broken lines in Figs. 1 and 3. This insert was essentially the same as that used in other work [6]. It extended 9·0 cm into each section, tapering from the tube diameter to a tip diameter of 5·1 cm.

Flow visualization

Before embarking on the heat-transfer experiments it was considered advisable to undertake a visual study of flow phenomena. In this way it would be possible to relate hydrodynamic effects to thermal effects and thereby offer a better interpretation of the heat-transfer results. Accordingly, models of the open and closed systems described above were constructed from plexiglass tube of the same diameter. They were heated and cooled by circulating water through concentric plexiglass jackets which did not obscure the view of

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*The terms *open* and *closed* are used in the usual sense for thermosyphons. Strictly speaking, they refer to the liquid only because the term *closed* in in conflict with *aeration*.

†Axial variations in wall temperature were kept well within 5 per cent of the overall temperature difference, for both open and closed systems.

the aerosyphon proper. The aeration system was identical to that subsequently used in the heat-transfer experiments.

EXPERIMENTAL RESULTS

Flow visualization

Flow visualization studies were conducted for both the open and closed systems. For the open system, experiments were carried out for a variety of arbitrarily-chosen orifices and air flow rates with bubble conditions ranging from laminar Stokes flows up to turbulent oscillatory flows. It soon became apparent that bubble behaviour could not be simply described even for a fixed orifice Reynolds number.

Of most interest were the turbulent boundary layer flows produced with oscillating bubbles as these were expected to produce the highest heat-transfer rates. The well-documented behaviour of such bubbles in isolation was found to be modified; partly as a result of coalescence and interaction with neighbouring bubbles in a non-uniform velocity field, and partly as a result of proximity to a solid wall. A particular note was made of the tendency of the bubbles to migrate towards the axis of the system. To offset this effect a number of inserts with wire mesh extensions were devised and tested. Their principal effect was to ensure that the bubbles in the heated section remained in an annular region and did not interfere too much with the descending central core.

A series of photographs was taken to record bubble behaviour above single orifices. Using appropriate exposure times it was found possible to measure both bubble diameter and velocity. In addition, long exposure times were used to produce bubble steaklines which revealed not only the individual bubble trajectories but the extent of the "annular" region through which they ran [see Figs. 6(a) and 7(a)].

Visual studies of the closed systems followed a similar pattern with additional attention being given to bubble behaviour in the upper section, with and without the coupling insert. Here again, the inward migration of the bubbles necessitated the use of a mesh cone extension on the insert in order to prevent bubbles from entering the outer annulus of the upper section. Photographic data on bubble characteristics were also obtained for the central core of the upper section [see Figs. 6(b) and 7(b)].

Heat-transfer experiments

Taking advantage of the insight provided by the visual flow studies, a series of heat-transfer experiments was undertaken with the brass aerosyphon. For the open system, this began with a study of single-phase behaviour in the turbulent boundary-layer region. The results obtained were found to be consistent with the comparable data of Martin [3] and Hasegawa *et al.* [4] and thus provided a confident base from which to enter the aeration studies.

Aeration experiments were then executed to determine the effect of air flow rate on the overall heat-transfer effectiveness of the system. Using orifice diameters of 0·813 mm and 1·57 mm tests were conducted for 4, 15, 31 and 62 equally-spaced holes. Figure 4 shows the results obtained with the overall heat flux fixed at 1080 W. The temperature difference used was the wall temperature minus the temperature recorded by the probe at the open end of the tube, i.e. $\theta = T_{WH} - T_{1H}$. In agreement with related experiments [3, 5] it was found that the axis temperature did not have a unique value in the vicinity of the mouth but the variations noted were not large enough to produce material changes in the heat transfer coefficient.

Several experiments were also carried out on the closed system with a fixed overall heat flux of 1090 W. For this system the appropriate temperature difference is well defined as the difference in the wall temperatures, i.e. $\theta = T_{WH} - T_{WC}$. The results are plotted in Fig. 5 for the particular orifice size and number indicated. As noted in the figure, one curve was obtained with an insert and the other without. The effect of inserts and mesh screens was in fact studied for both open and closed systems but a detailed discussion is considered beyond this paper.

In plotting Figs. 4 and 5 it was assumed that the properties of air remained constant at their values tabulated for a temperature of 24°C. Water properties were calculated at the temperature of the heated wall.

DISCUSSION AND CONCLUSIONS

Flow visualization

With a small orifice diameter (0·813 mm) it was found that the bubble train exhibited pronounced oscillations. Computation of the orifice Reynolds number showed it to be slightly under 400 which suggests oscillatory behaviour for single bubbles in the absence of a neighbouring wall. It thus appears that bubble flow regimes are not substantially changed by conditions in an aerosyphon. However, as mentioned earlier, the bubbles did have a tendency to oscillate gradually towards the tube axis as may be seen from Fig. 6(a). Clearly, if the effective span of the bubble trajectories is too great the return flow in the central core will be impeded. To avoid this might restrict the tube length or necessitate the use of a series of deflectors. It was found that wire mesh deflected bubbles but allowed liquid to penetrate thus controlling one without producing much effect on the other.

Increasing both the orifice diameter and the air flow rate by a factor of approximately two produced the

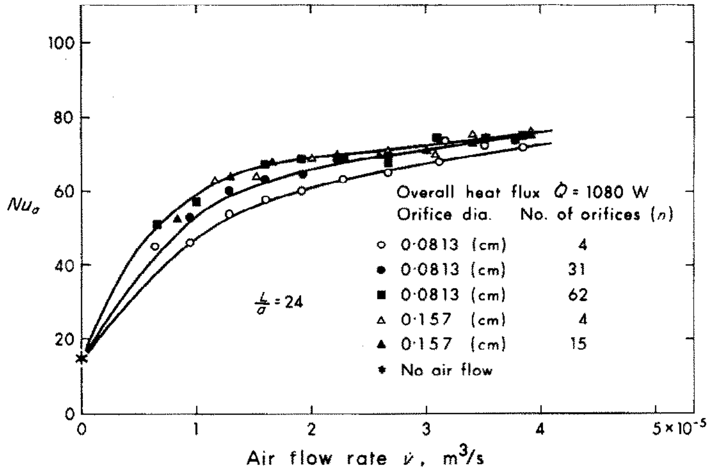

FIG. 4. Effect of air flow rate: open system.

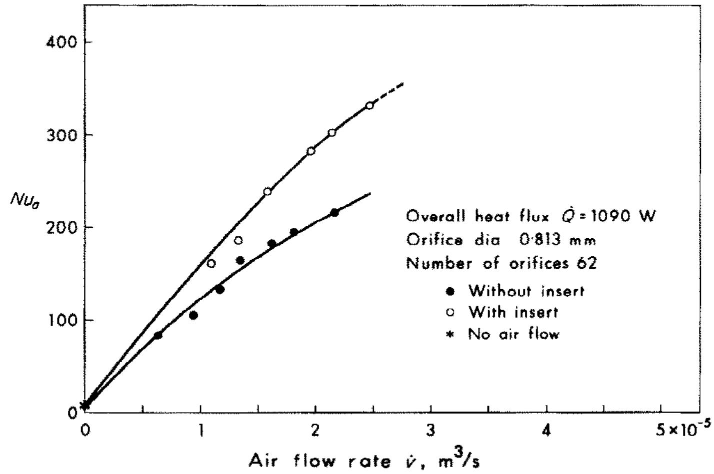

FIG. 5. Effect of air flow rate: closed system.

flow shown in Fig. 7(a). The orifice Reynolds number has increased only marginally and again suggests an oscillatory bubble motion. It is evident that the amplitudes of oscillation have decreased significantly thereby producing a well defined "annular" region.

Closed aerosyphon behaviour is indicated by Figs. 6(b) and 7(b). These photographs were taken with the insert, or coupling, in position so that an upward annular flow from the lower section is automatically channelled into the core of the upper section whilst the annular flow from the upper section becomes the lower section core. The photographs illustrate the effectiveness of the insert and again reveal the greater lateral migration of bubbles at the lower flow rate.

Heat transfer

The effect of air flow rate on overall heat-transfer coefficient in the open system is shown in Fig. 4 from which it is apparent that aeration increases the thermal effectiveness of the system by as much as an order of magnitude. As expected, the heat-transfer coefficient initially increases with air flow rate. Whether this trend would reverse at much higher flow rates is uncertain: a large void fraction and circulation deterioration suggest a reversal. The effect of the number and diameter of the orifices is seen to be slight over the range considered. Increases in either of these apparently produce slight improvements in heat transfer.

The data shown in Fig. 4 were obtained with the

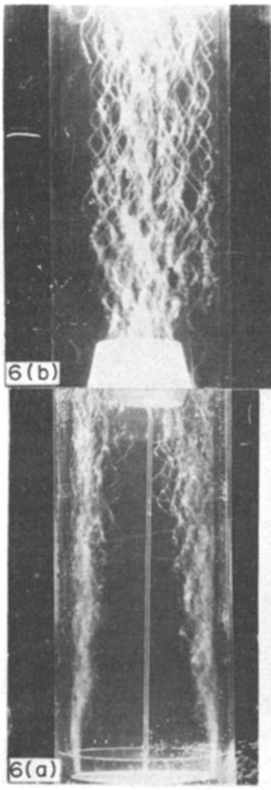

Fig. 6. Aeration at lower flow rate in closed system: (a) lower section; (b) upper section.

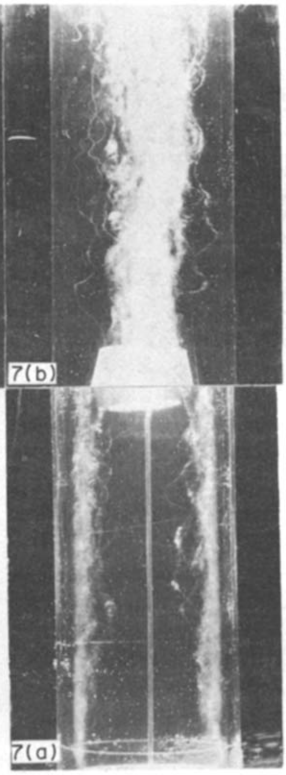

Fig. 7. Aeration at higher flow rate in closed system: (a) lower section; (b) upper section.

overall heat flux held constant at 1080 W. Increases in the air flow rate in fact led to decreases in the temperature difference across the system thus generating higher heat-transfer coefficients. This behaviour is illustrated in Fig. 8 which compares open aerosyphon data (circles) with those previously obtained for thermosyphons. As expected, the data fall on a curve sloping upwards to the left. Surprising, perhaps, are the Nusselt number magnitudes which are seen to be comparable with those for boiling closed thermosyphons. It is quite likely that even higher heat-transfer coefficients could be obtained because examination of local heat flux and visual flow data indicated that the returning central core was impeded near the mouth of the tube.

The effect of air flow rate on the overall heat-transfer coefficient in the closed system is shown in Fig. 5. As one might expect, the same monotone trend is noticeable although the data given are not too extensive. The insert is seen to have a beneficial effect implying that its absence permits mixing at the junction between the heated and cooled sections and possibly throughout the entire top half of the tube. Obviously, mixing reduces both the water circulation and the internal temperature gradients. For these reasons the beneficial effect of the insert could be lost if its collection gap was exceeded by the thickness of the rising aerated annulus of water.

A striking, and unexpected, feature of the closed system is the fact that the heat-transfer coefficients actually exceed those of the open system. This is clearly seen in Fig. 8 which also reveals that the closed aerosyphon data (triangles and squares) lie well above comparable data obtained for the boiling thermosyphon. The only plausible explanation of why the closed aerosyphon is superior to the open aerosyphon appears to lie in the earlier suggestion that the latter system was operating well below its full potential where mixing is absent. This suggestion is in accord with Japikse's speculation on single-phase systems [5]. Explaining the gap between the aerated and boiling results is more difficult because the respective sets of data were obtained with different tube lengths and diameters: both length–diameter ratio and bubble-tube diameter ratio cloud the issue. Furthermore, the Nusselt number is not particularly appropriate to

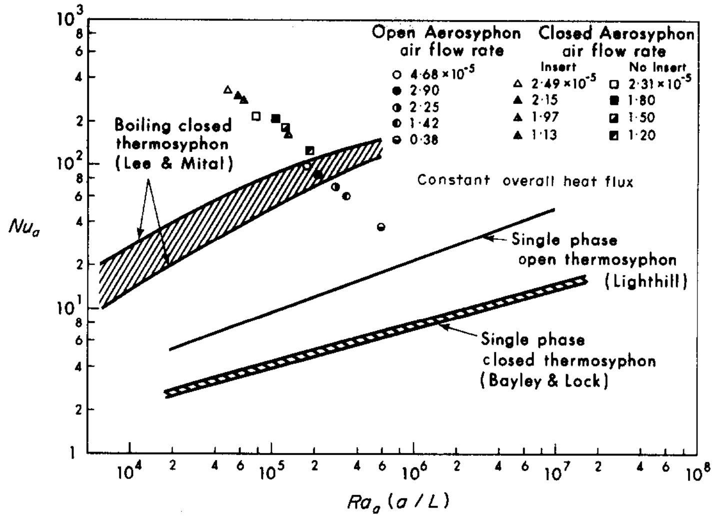

FIG. 8. Comparison with thermosyphons.

boiling data. It is tempting to suggest that the dominance of circulatory control over the latent heat effect is the key factor but, although this would appear to be consistent with barbotage/boiling comparisons, it must remain a speculation at this stage.

The use of aeration removes one of the natural advantages of the thermosyphon—the fact that no operating power need be supplied—and it is therefore logical to enquire whether the improved heat-transfer rates are in fact real gains. It is impossible to give a general answer to this question because the costs and characteristics required vary considerably from application to application. Among the various attributes in favour of aeration, two are especially worthy of mention. The first, which is the more obvious, is the substantial increase in heat flow which can be produced by the relatively small power supplied in the air. Since both the heat flux and the air flow rate are variables it is evident that the ratio of air power* ($\dot{W}$) to thermal power ($\dot{Q}$) is also a variable. In the work recorded here, this ratio varied from zero up to a maximum of 1 per cent, thus demonstrating the high "leverage" which is possible.

The second principal advantage of aeration is the control which it provides on a system which is otherwise controlled entirely by the overall temperature difference. The simple thermosyphon is roughly analogous to the electrical semi-conductor: a (thermal) potential difference can generate a large (thermal) current if applied one way across the device but produces only a negligible current when applied in the opposite direction. Such a "thermal diode" is converted into a "thermal triode" by aeration which, for a given temperature difference, acts to "amplify" the heat flux. Of course, this is only a crude analogue but it does serve to illustrate how the aerosyphon is capable of control: either independently of the overall temperature difference or, by means of a suitable feedback loop, with the heat flux behaving like any (reasonable) desired function of the overall temperature difference.

The purpose of this paper was to present an initial study of the aerosyphon in which the *modus operandi* and heat-transfer characteristics have been explored. The high Nusselt numbers recorded for the open and closed systems offer great promise for the application cited earlier and may generate new applications. However, it is very apparent that aerosyphon behaviour is not fully understood and the device deserves much more attention.

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L'AEROSYPHON: UNE ETUDE EXPLORATOIRE

Résumé—L'article constitue une étude expérimentale du thermosyphon à gaz ou aérosyphon. Ce travail comprend une visualisation de l'écoulement et une série d'expériences sur le transfert thermique de façon à comprendre le phénomène et de déterminer les caractéristiques du transfert thermique peu connu.

DER KOHLENSÄURESYPHON: EINE GRUNDLEGENDE STUDIE

Zusammenfassung—Der Aufsatz beschreibt experimentelle Untersuchungen über den kohlensauren Thermosyphon oder Kohlensäuresyphon. In Verbindung mit optischen Strömungsuntersuchungen wurde eine Reihe von Wärmeübertragungsexperimenten in der Absicht durchgeführt, den modus operandi des Geräts zu verstehen und sein ungewöhnliches Wärmeübertragungsverhalten zu erforschen.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ АЭРОСИФОНА

Аннотация — В работе проводится экспериментальное исследование термосифона с насыщенным газом, т. е. аэросифона. Течение в сифоне изучается с помощью визуализации потока; проводится также серия экспериментов по теплообмену для выяснения принципа работы устройства, и исследуются аналогии в характеристиках теплообмена, присущие рассматриваемому устройству.