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SINGLE-PHASE TRANSPORT PROCESSES IN THE CLOSED THERMOSYPHON

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Abstract—The results of two experimental studies with flow visualization and heat-transfer measurements are presented for ordinary liquids under vertical and inclined conditions. The mid-tube exchange process, at the confluence of the rising boundary layer from the heated end and the falling boundary layer from the cooled end, was found to be basically convective in nature with conduction and mixing playing important secondary roles. The effect of increasing the overall temperature difference or decreasing the Prandtl number was to increase the importance of mixing until it predominated. Under conditions for which impeded flow in an open thermosyphon would be obtained, it was found that boundary-layer flow is maintained in the closed thermosyphon thus allowing the overall efficiency of the closed thermosyphon to approach that of the open thermosyphon. The effect of inclination was found to enhance the convective exchange mode, with complete loop circulation at moderate angles, thereby causing increased heat transfer. Accurate prediction methods for vertical behavior and trends for inclined behavior are given. The semi-closed system, used recently (by Ogale, Delft) in a rotating turbine blade model, is reviewed.

NOMENCLATURE

a, tube radius, inside;
A, property groupings;
b_i, ordinate intercept value of certain linear correlations;
C, convection temperature parameter;
C_p, specific heat (at constant pressure);
d, tube diameter, inside;
g, gravitational acceleration;
h, convective heat-transfer coefficient;
k, thermal conductivity;
L, tube length of the open thermosyphon or half-length of the closed thermosyphon;
$\dot{m}$, mass flow rate, non-dimensional $= \dot{M}C_p/kL$;
$\dot{M}$, mass flow rate, dimensional;
M_i, slope values of certain linear correlations;
q, heat flux;
$\dot{Q}$, heat flow;
r, radius, non-dimensional $= R/a$;
R, radius, dimensional;
T, temperature, dimensional [°C];
ΔT, temperature difference;
α, thermal diffusivity $= k/\rho C_p$;
β, coefficient of thermal expansion or the (complementary) thermal boundary-layer thickness from tube centerline, depending on specific application;
δ, momentum boundary-layer thickness from tube centerline (complementary);
θ, angle of inclination;
μ, viscosity, dynamic;
ν, viscosity, kinematic;

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ξ, convection effectiveness parameter;
ρ, density;
σ, centerline temperature defect;
χ, mixing temperature parameter.

Nondimensional groups

Gr, Grashof number $= \beta g \Delta T a^3/\nu^2$;
Pr, Prandtl number $= \mu C_p/k$;
Ra, Rayleigh number $= Gr. Pr$;
Nu_a, Nusselt number (used for open system) $= ha/k = \dot{Q}/2\pi(T_1 - T_0)k$;
Nu_d, Nusselt number (used for closed system) $= hd/k = \dot{Q}/\pi(T_{1,1} - T_{1,2})k$;
t, $\beta g a^4 T/\nu\alpha L$;
t_{ot}, $\beta g a^4(T_1 - T_0)/\nu\alpha L$;
t_{ct}, $\beta g d^4(T_{1,1} - T_{1,2})/\nu\alpha L$.

Subscripts

a, based on radius;
b, condition at the base;
ct, closed thermosyphon;
mc, mixing cup (temperature);
ot, open thermosyphon;
1, condition at wall;
0; condition at orifice on the centerline;
1, 2, denotes bottom or top half respectively of closed thermosyphon; when paired subscripts are used the second number always denotes the tube half.

1. INTRODUCTION

DURING the past 20 years both open and closed thermosyphons have received considerable attention, but the closed system presently is of greatest interest for applications and yet has been studied the least [1]. A closed system is currently being evaluated for application to turbine blade cooling at the Technological University of Delft and initial reports are encouraging [2]. Recently a review of this problem was given [3]. Other applications, such as the cooling of thermal devices ranging from nuclear reactors to bakers' ovens [4] have been discussed in the literature over the past years. Of peculiar interest are the applications for preserving permafrost under buildings in the Canadian northland [5] and for understanding the temperature distribution in earth drillings in steam power fields in New Zealand [6, 7].

Although several studies have been made which relate to the closed system (see [7]) only the work by Lock [8], also reported later by Bayley and Lock [4], is directly pertinent to a fundamental understanding. Heat transfer rates were measured in an opaque test cell for glycerin, ethylene glycol, water and air for length to radius ratios of 7·5, 15 and 22·5. The basic flow regimes were reported to be the same as those observed in the open thermosyphon for both laminar and turbulent flow (i.e. a boundary-layer regime, an impeded non-similarity flow regime, and a similarity flow regime with or without a stagnant bottom region being theoretically possible). The most unusual result was that there appeared to be an optimal Prandtl number for heat transfer in the closed thermosyphon. Three idealized mid-tube exchange processes were portrayed which permitted either (1) direct convection from a boundary-layer regime to the opposing core or (2) a complete mixing of the colliding boundary layers or (3) only conduction across the mid-plane with no mass transfer across it. The authors expected elements of all three to be present in practice and found some experimental evidence to support particularly the first two.

2. EXPERIMENTAL PROGRAM

The experimental results to be presented are based on two studies conducted both (1) to determine the nature of the fluid flow and temperature distributions [7], and (2) to determine the corresponding heat-transfer rates [9], under both vertical and inclined conditions with various thermal boundary conditions. Thus a transparent test cell, Fig. 1, and an opaque test cell with electrical heating, Fig. 2, were designed and built. Each apparatus had the same internal dimensions; a 2 in. i.d. and a 16 in. length and equal heated and cooled lengths.

The transparent test cell, made of Plexiglas, used two annular sections to permit heating the bottom and cooling the top tube halves. These annuli were supplied with constant temperature water from high quality thermostats. The top section of the opaque apparatus was similarly cooled but the bottom half employed four independently controlled electrical heaters. These heaters allowed control over the lower wall temperature distribution and were, of course, both insulated and calibrated so as to control conduction losses. Thus an accurate heat-transfer rate could be measured. The end boundary conditions of each apparatus were nominally insulated and were established by using good insulators which directly formed the thermosyphon ends.

Both systems employed a two point gradient wall thermocouple scheme which could be accurately calibrated to give the inside wall temperature to within ± 1 per cent of the operating temperature difference. Also, each apparatus had a thermocouple probe for measuring radial and/or axial temperature

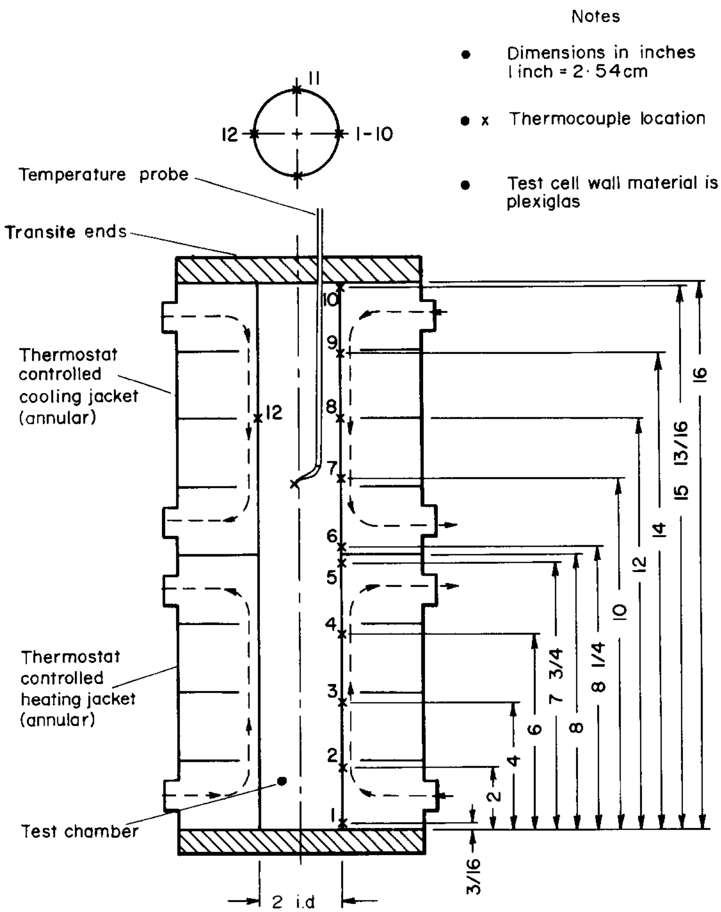

FIG. 1. Schematic drawing of the transparent closed thermosyphon apparatus. Dimensions in inches, 1 in. = 2·54 cm.

distributions. The temperature probe, having a maximum volumetric displacement of 0·4 per cent, gave negligible flow interference. A digital voltmeter data acquisition system with a measurement capability to 0·1 μV (0·01°C in practice) was used which gave fairly continuous time–temperature traces. Dye injection, fish flakes and a tracer method were used taken to assure that no interference with the actual flow process occurred.

For the transparent test cell several limiting factors had to be considered in planning the experiments. Due to the low thermal conductivity of the Plexiglas test cell ($k \simeq 0·0004$ cal/s cm °C), sizeable temperature drops occurred in the test cell wall, between the annulus and

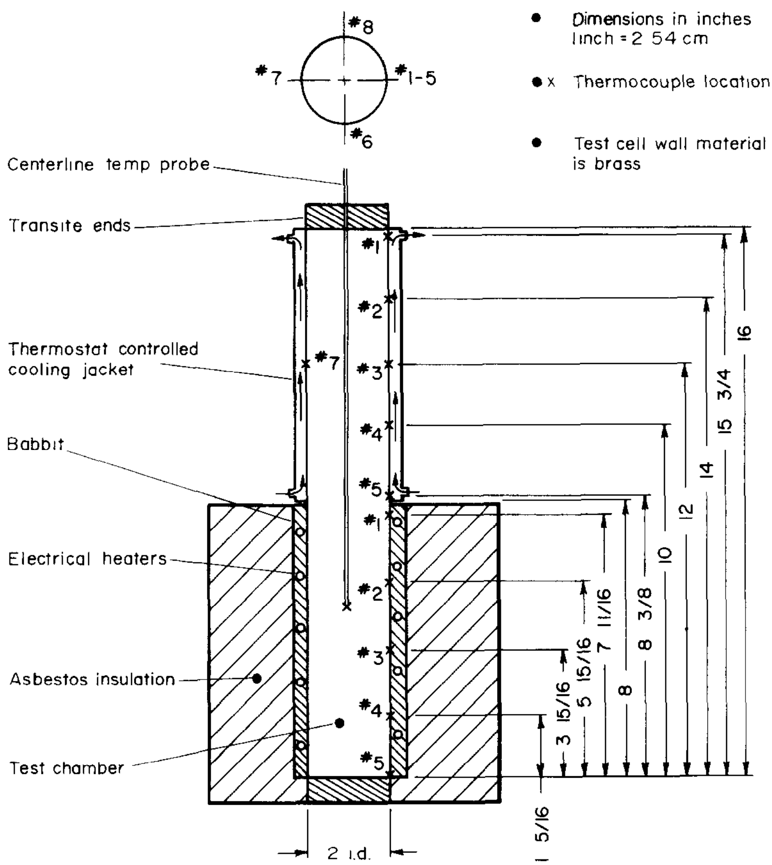

FIG. 2. Schematic drawing of the opaque closed thermosyphon apparatus. Dimensions in inches, 1 in. = 2·54 cm.

to obtain various types of flow visualization. These methods are reviewed in [10] and discussed in detail in [7]. In all cases the amount of alien indicators was never more than 0·01 per cent of the test fluid and had negligible influence on fluid properties. Due care was test fluid. Rough calculations showed that the maximum attainable inside wall temperature difference, ΔT, would be about 12–14°C, thus requiring a temperature measurement accuracy of about 0·01°C. The upper limit on temperatures was set by Plexiglas strength characteristics and the lower limit by the problem of effective heat removal. Hence large variations in t_{ct} could not be obtained by varying the temperature difference and careful choices of fluid properties were necessary to get these t_{ct} variations. Table 1 shows the range of t_{ct} and Pr covered. The basic tests consisted of ten experiments for which careful temperature field measurements and flow observations were made. Five other miscellaneous tests with glycerin and methyl alcohol were conducted to extend the observations of the basic ten. Nominal values of ΔT of 1·00, 3·00 and 9·00°C were used. All fluids used were checked for chemical compatability with Plexiglas by placing a sample of Plexiglas in a beaker of the fluid. Unfortunately, this test failed to reveal a subsequent mishap. When alcohol was first used as a test fluid noticeable cracks or fissures appeared in the test cell wall after the apparatus top was secured and drawn up tight. Later investigations revealed that alcohol causes a cracking process that relieves stresses imparted by compression or occurring naturally as in extruded tubing. Hence all alcohol tests were postponed until the end of the study to avoid further damage. The cracks can be seen in later photographs, and although they appear to be bad in some pictures (tube curvature causes considerable magnification) they could not be felt on either the inside or outside of the tube, hence causing no surface problems, and an accurate calibration of the wall thermocouples both just prior to and after the cracking revealed no changes. Hence the test cell was continued to be used in spite of its appearance.

Table 1. Experimental conditions in transparent test cell.

Experiment number	Fluid*	$t_{ct} \times 10^{-5}$	T_1(°C)	ΔT,(°C)	Pr
	0	0·032	30	1·0	5100/5500
	0	0·10	30	3·0	5100/6500
	0	0·58	38	9·0	2810/5500
1	3	1·66	30·00	0·98	132/137
2	2	4·90	30·00	0·90	16·9/17·4
3	1	8·09	30·04	1·02	5·4/5·5
4	3	5·11	30·00	3·02	132/149
5	2	15·8	30·00	2·91	16·9/18·4
6	1	23·6	30·01	3·01	5·4/5·8
7	4	2·48	38·00	8·98	564/936
8	3	21·6	37·96	8·99	98·2/138
9	2	71·8	38·17	9·22	13·5/17·4
10	1	102	37·96	9·14	4·5/5·6
	00	170	30	3·0	6·5/6·7
	00	630	38	9·0	6·0/6·6

* Fluid No. 00 is methyl alcohol, No. 1 is water, No. 2 is 35% glycerine/65% water, No. 3 is ethylene glycol, No. 4 is 90% glycerin/10% water, and No. 0 is glycerin.

For the opaque test cell no particular limitations existed and experiments were conducted using water as a test fluid with $6·2 < \log t_{ct} < 8·3$ and $1·9 < Pr < 6·1$. Thus trends observed in the transparent tests could be extended and corresponding heat transfer rates could always be determined.

The particular operating procedures used have been recently described elsewhere for the transparent apparatus [10] and in the case of the opaque apparatus the procedures were extremely similar to all previous thermosyphon investigations.

3. FUNDAMENTAL BEHAVIOR OF THE VERTICAL SYSTEM

3.1 *Observed flow process*

The fundamental flow process, in the sense of basic stable laminar flow, which was observed to exist is illustrated in Fig. 3. This illustration forming a cluster of warm (or cool) streams in the cool (or warm) tube halves. Fluid which came down the wall directly counter to a dominant flow stream is returned to its original tube half and can form a stable vortex as illustrated in Fig. 3. The complete flow pattern is basically stable laminar flow although a small rotational realignment of the flow streams was found after several hours. No significant mixing was observed although small fluid elements were sheared off into an alien region on occasion.

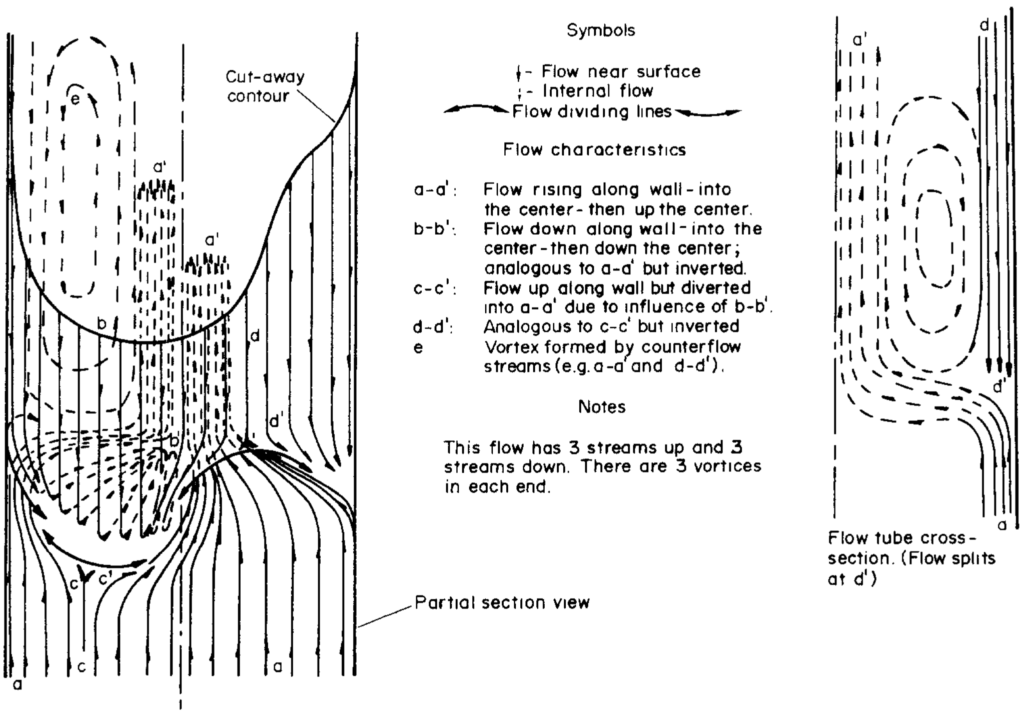

FIG. 3. Steady laminar flow convective exchange mechanism.

shows that the mid-tube exchange mechanism involves the creation of flow streams from the boundary layers in the vicinity of the tube mid-section. The flow streams slightly penetrate the opposite boundary layer and are subsequently bent into a horizontal direction so that they proceed radially toward the tube center. At the centerline they are diverted once again so that they continue in their original axial direction

These flow observations were made using dye injection and fish flakes. Figure 4 is a set of photographs showing elements of the general exchange mechanism displayed in Fig. 3. Parts a, b, c, d and f are dye traces and it should be noted that two types of dye marks can be observed. First, regions of very low or zero velocity, which must occur between adjacent streams of opposite direction, tend to accumulate

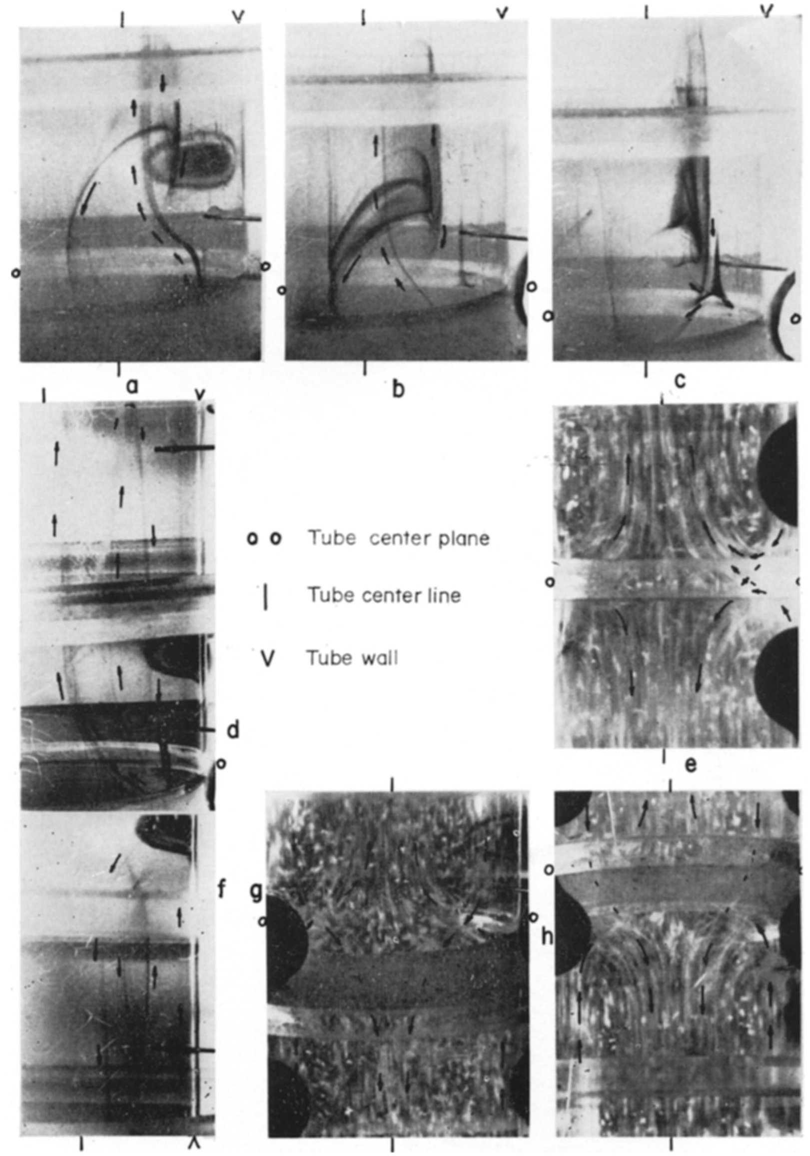

FIG. 4. Photographs of exchange mechanism observations.
a, b, c, d — Dye traces showing the convective stream, Exp. No. 7.
e, g, h — Time exposure of fish flakes showing convective nature, Exp. No. 4.
f — Dye trace showing standing vortex, Exp. No. 7.
Notes: 1. The dark circles are inlet fittings into the annular region, not into the test cell proper (tube)
2. The horizontal bands are flow dividers in the annulus only.

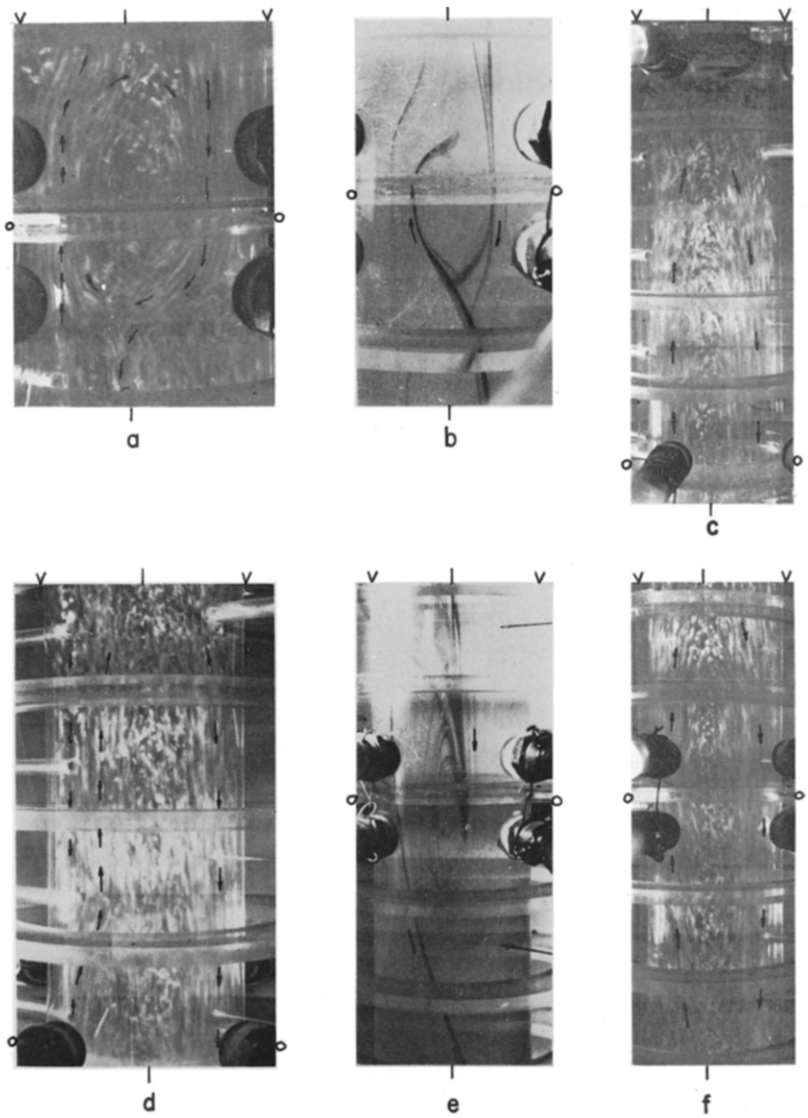

FIG. 8. Photographic flow observations in the inclined thermosyphon.

a — $\theta = 6°$	Experiment No. 4.
b — $\theta = 6°$	Experiment No. 7.
c — $\theta = 12°$ or $18°$	Experiment No. 4.
d — $\theta = 6°$	Experiment No. 4.
e — $\theta = 12°$ or $18°$	Experiment No. 7.
f — $\theta = 12°$ or $18°$	Experiment No. 4.

Notes:
1. The dark circles aıe inlet fittings into the annular region, not into the test cell proper (tube).
2. The horizontal bands are flow dividers in the annulus only.
3. The shining streaks are due to glare.

° ° Tube center Plane
| Tube center Line.
V Tube Wall.

and hold the dye stagnant. Thus a partial shell or tube is shown through which the actual flow stream travels (a, b, c, d). Secondly, the dye will follow a basic flow stream as shown in the photographs (a, b, d, f). Pictures e, g and h are fish flake time exposures and show the general fluid motion. Pictures g and h seem to show that two flow streams merge to flow through a given opening but these are actually just high velocity portions of a single flow stream being formed as was observed directly. These portions accelerate greatly so as to pass through the restricted flow tube.

For the example shown in Fig. 3 only three streams up and three down were observed. However, as few as two up and two down and as many as approximately ten up and ten down were also observed. It was found that the number of streams increased as Pr decreased or ΔT increased and the stability of the exchange process likewise deteriorated. Even after flow streams could no longer be seen evidence of convection still existed in the centerline temperature profile giving a clear step at the exchange region.* To be sure, this process which is convective in the fundamental sense is not independent of other exchange mechanisms. For conditions of high viscosity and/or low temperature differences, definite evidence was found of conduction by comparing the temperature found in the core on one side of the exchange region with what would be expected based on the thermal conditions of the opposite boundary layer. By the same method and by direct observation evidence was found of considerable mixing effects as Pr decreased or ΔT increased.

The importance of the Prandtl number cannot be over-stressed. For cases where $Pr > 90$ the flow was stable. For $10 < Pr < 20$, the convective nature was apparent but the streams were unstable and shifted around every few minutes. When Pr was less than 10, the convective process was basically unstable and shifted continuously by itself. Increasing the temperature difference aggravated this condition until no streams could be seen.

A comparison between the observed exchange region and the inlet region of the open thermosyphon sheds further light on both systems. Such a study for the open system was performed by Martin and Lockwood [11] (see Fig. 9 of [1] for the flow pattern). For low heat fluxes and very viscous fluids, they reported that the existing hot fluid annulus necked down to form a hot rising stream just after leaving the orifice. The cold fluid which had to flow down the core, and which came from the floor of the reservoir, pierced this hot annular cone of fluid and entered the core through egg-shaped holes. Indeed this is similar to the process observed in the closed thermosyphon. However, a fundamental difference exists in the stability of the two processes. Under the conditions just mentioned for the open thermosyphon study, the egg shaped holes had a random variation in size and orientation (but the flow area involved appeared to remain constant). This is the opposite of the result in the closed system where only a slight shift was found after several hours. It is thus seen that the presence of the tube walls has a stabilizing effect on an otherwise similar process.

Finally an important aspect of this exchange process would appear to be the role which thermal instability plays. Bayley and Lock [4] stated that this should be a significant factor and Lock in later correspondence to the authors suggested that if the top half were heated and the bottom half cooled, it might well be possible that no convective cross-over would exist. Presumably their thoughts on thermal instability in the exchange region are valid; but inasmuch as only the case of $T_1 > T_2$ was considered in this study there was always mass transfer across the tube center plane.

* In an additional report on this part of the study [10] some radial and axial temperature profiles were given as well as a case by case accounting of the experimental runs.

3.2 *Measured heat transfer results*

Regarding the previous section, the heat-transfer data confirmed the concept of a convective mechanism at low temperature differences with secondary losses in that the measurements obtained were higher than what would be expected assuming pure mixing and lower than what would be anticipated under conditions of pure convection. On this basis too and based also on centerline temperature measurements, it was found that the change over from the fundamentally convective exchange process to a mixing mechanism becomes rather complete for larger temperature differences, in this case corresponding roughly to the point where transition to turbulence occurs.

Comparison of the laminar results, see Fig. 5, up to $t_{ct} = 10^{7\cdot6}$ with the very similar case from [8] shows some disagreement, which will

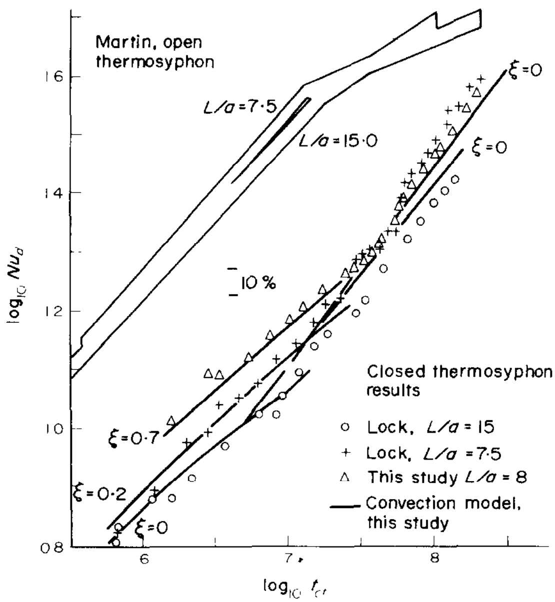

FIG. 5. Heat transfer in open and closed thermosyphons with water: $\Delta T_{ot} = T_1 - T_0$ and $\Delta T_{ct} = T_{1,1} - T_{1,2}$.

be properly treated in part 3·5. Of particular interest now are the results for $t_{ct} > 10^{7\cdot6}$ which correspond to turbulent flow. In interpreting his results, Lock claimed to have found both a turbulent boundary layer and fully turbulent impeded flow. The latter might be a mistake, or at least an overstatement, however, since the results do not show any significant reduction in heat-transfer rate as one finds in the open thermosyphon under impeded turbulent flow conditions (also shown in Fig. 5) where the rate nearly flattens out, so to speak, and where a turbulent boundary-layer flow is never ultimately obtained.

It must be acknowledged that, although the heat-transfer rates in Fig. 5 do not show strong evidence of impeded flow, some such effects are surely present. For the visualized experiments some definite core-boundary layer mixing was observed (but generally restricted to the outer parts of the boundary layer) and a considerable amount of churning and mixing were evident in the exchange region for conditions approaching and including transition to turbulence. Although these factors can well lead to impeded flow, a convective type centerline temperature profile still existed, in the observation tests, so the extent of this interaction could not have been too significant. However, in the heat-transfer apparatus with turbulent flow, the centerline temperature profile changed from a constant temperature mixing case to one where the temperature was high at the bottom (in the core) and low at the top, which could only be caused by adverse core-boundary layer mixing, the very cause of the low heat-transfer rates in the open thermosyphon under impeded conditions. Thus some evidence of the causes of impeded flow were found but no evidence of a strong effect was present as judged by comparing the heat-transfer results against those corresponding to open thermosyphon behavior from Martin [12] (Fig. 5).

This absence of strong or definite impedance, which does occur under the same conditions in the open system, is in all likelihood due to the strong difference in stability found in the otherwise rather equivalent orifice (open system) and mid-tube exchange region (closed system). In the former case the large fluctuations present may well be the cause of the strong adverse impeded phenomena, as anticipated in the earliest thermosyphon analysis by Lighthill [13]. As a consequence of this fundamental stability difference, Fig. 5 clearly shows that the performance of the closed system can approach, and perhaps eventually exceed the performance of the open system—in spite of the inefficiency inherent in the mid-tube exchange region.

Whether or not the performance of the closed system would actually exceed that of the open system would, of course, depend on whether or not strong impedance would also develop. All studies to date are insufficient to determine this completely.

3.3 *New analysis of previous heat-transfer data*

A new analysis of Lock's heat-transfer data* was conducted by using the reported heat fluxes and wall temperatures to calculate equivalent centerline temperature distributions, with the aid of the open thermosyphon study described in [1]. These centerline values were, generally, not available in the original study. The results, for laminar boundary layer cases only, are as follows:

(1) The vast majority of cases showed $T_{0,2} > T_{0,1}$ or in other words the effect of convection was stongly evident. Pure convection (giving $T_{0,2} = T_{mc,1}$) was not found.

(2) There were certain cases for which $T_{0,1} \simeq T_{0,2}$ and thus some evidence for a mixing mechanism was found. These results occurred most readily in long tubes (constricted flow) and/or for low viscosity fluids with small or moderate temperature differences. Generally, however, one would expect this mechanism to occur for large temperature differences and thus outside disturbances might have been present.

(3) A number of cases in the longest tubes showed $T_{0,1} > T_{0,2}$ or the opposite of a convection profile. Presumably these are the result of the adverse effect of core-boundary layer interaction which should be strongest in long, thin tubes. However, as the temperature difference increased, this effect diminished and convective profiles were again found.

(4) For the glycerin experiments, interesting results were obtained. In the top half, based on $T_{0,2} - T_{1,2}$ the results fell in the range $80 < t_{ot} < 2600$. Hence boundary layer flow (by comparison to the findings of [12] or [13]) was never obtained in this half of the tube but rather laminar impeded flow. Thus Lock's low heat-transfer results for glycerin are understandable and there is no reason to believe that there is an optimal Prandtl number for laminar boundary-layer flow.

3.4 *Transition to turbulence in the closed thermosyphon*

In the transparent test cell transition was found to occur for $t_{ct} \simeq 10^{7\cdot 2}$ or $Ra_L \simeq 10^{9\cdot 6}$ (with $Pr = 6{\cdot}5$) and transition values of $t_{ct} \simeq 10^{7\cdot 6}$ or $Ra_L = 10^{10\cdot 0}$ (with $Pr = 5{\cdot}4$) were obtained in the opaque test cell. In each case, transition was found to involve only boundary-layer flows.

These results are in reasonable agreement with those found by Lock for transition with water (see Fig. 7 of [1]). As mentioned previously, however, his prediction of an impeded regime could not be clearly confirmed in so far as heat-transfer rate trends were concerned. Considering Fig. 6 (using Lock's ethylene glycol data) in particular, much of this problem can be explained. Any such plot, with Nu_d vs. t_{ct}, is compiled with the properties used in these parameters evaluated at one given temperature, the current convention being the use of $T_{1,1}$. This implies, however, that $T_{1,2}$ is now an independent parameter in so far as good property modeling is concerned. It was stressed before that the properties, particularly Pr, are extremely important for understanding the closed system and the section in this paper concerning modeling will show that both $T_{1,1}$ and $T_{1,2}$ are necessary for a good representation. It was found upon re-examination of the data in

* The authors wish to thank Professor G. S. H. Lock for his assistance on several occasions and for making his data available in a form suitable for this analysis.

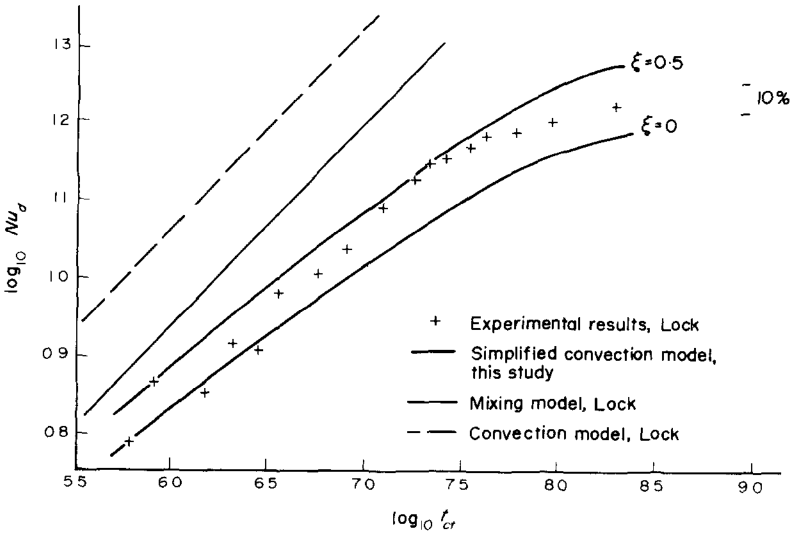

FIG. 6. Closed thermosyphon heat transfer with ethylene glycol: Theory and experiments, $L/a = 22{\cdot}5$.

Fig. 6 that when a shift in the data occurred, there had invariably been a definite change in $T_{1,2}$ which was otherwise only slowly varying. In fact, the "scatter" in Fig. 6 can be traced, point by point, to increases and decreases in $T_{1,2}$ except the last several points which may finally be affected by impedance in this (longest) tube. This $T_{1,2}$ effect was generally apparent near the points where transition and the onset of impedance were reported to occur for all L/a cases in [4]. Indeed, all the ethylene glycol heat-transfer results showed only small changes from what might be expected theoretically for laminar flow.

3.5 *Influence of end thermal boundary conditions*

With simple thermodynamic considerations it can be shown that the end conditions can strongly influence both the amount of heat transfer and the stability of the core region (hot fluid under cold fluid gives rise to instabilities). Indeed, experiments conducted with non-conducting (transite) and then conducting (copper) plugs at the tube ends showed an increase of 6–7 per cent in heat transfer for laminar flow and 12–15 per cent for turbulent flow. These numbers would be higher if the contact resistances had been absent, a fact which probably also prevented serious adverse stability effects from occurring which would cause core-boundary layer mixing and subsequent heat transfer reduction.

A careful examination of Fig. 5 shows, however, that the adverse influence of the conducting base instability probably existed in Lock's study where end conduction effects were also present. His heat-transfer results were lower than those measured in this study, with a nominally adiabatic base, and, if due to the end effect, this could only be explained by the adverse stability problem as opposed to the normally favorable heat-transfer condition. This argument is corroborated by Fig. 7 which shows a comparison between centerline temperature distributions from the two studies. In each case a convective profile exists giving higher temperatures in the cold end than occurs before the step in the hot end. Thus significant impedance effects arising either from the mid-tube exchange mechanism or core-boundary layer interaction must have been absent since such effects work to destroy a convective profile and preclude flat profile sections. The end portions, however, show a significant difference and the nominally insulated case (this study) shows only a small shift (toward ambient) due to conduction losses whereas the case from

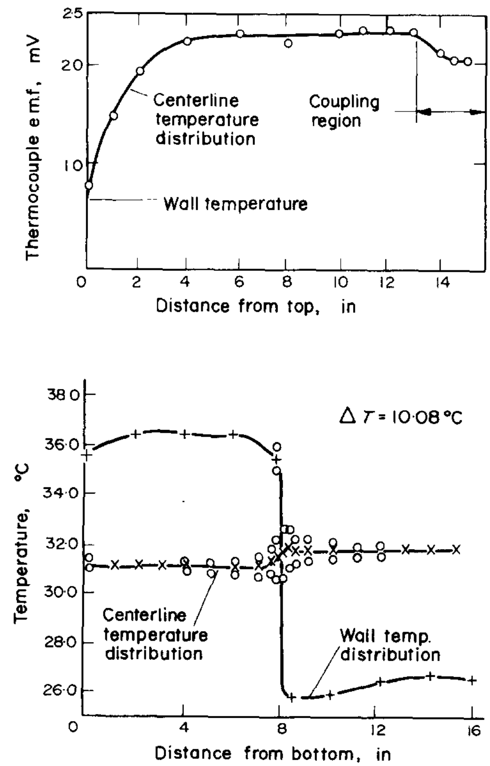

FIG. 7. Centerline temperature profiles in water: This study (below) for an adiabatic base and Lock [8] for a conductive base (above).

Lock shows that the end has very nearly assumed the adjacent wall temperature. Presumably such a core profile with rather gradual curvature would imply definite end mixing as opposed to just conduction and hence the inherent end instability has had a strong influence on degrading the overall heat-transfer rates.

3.6 *Experimental basis for a closed thermosyphon performance model*

This study has also found several basic facts which justify treating the closed thermosyphon as two open systems joined together. First of all, no significant differences were found in the measured radial temperature profiles between the open and closed systems (see the results given in [7] or [10]) and, secondly, local laminar boundary layer heat transfer results were quite comparable (see [9]). Although this experimental justification was made for $L/a = 8{\cdot}0$ only, it should provide a starting point for analytical studies.

4. FUNDAMENTAL BEHAVIOR OF THE INCLINED SYSTEM

4.1 *Observed flow process*

The flow visualizations were made with the apparatus tilted so that the centerline was inclined up to eighteen degrees from the vertical, this angle being denoted as θ. The observations were made for all fluids at temperature differences of three and nine degrees using fish flakes and dye. A basic behavior pattern was found in all experiments. Certain differences, attributable either to increasing ΔT or decreasing Pr, were also found and will be discussed in the latter half of this section.

Observations made at $\theta = 1{\cdot}5$, 3 and 6° showed that the initial effect of inclination was to cause a gradual rearrangement of the convective exchange mechanism for the more viscous fluids and a gradual alignment of disorganized fluid streams for the less viscous fluids. In cases where a steady convective exchange mechanism existed for $\theta = 0°$ the first development at small inclinations was the thickening of a single flow stream (one passing from the lower boundary layer into the upper core) along the (upper) leading edge and an analogous but opposite effect on the (lower) trailing edge. The thickened flow stream would penetrate the opposing boundary layer a bit further than for $\theta = 0°$ and slant more gradually on over into the core. With larger inclinations the two preferred flow streams became larger, flowed faster, and penetrated the opposing boundary layers further. At $\theta = 6°$ only two flow streams were left, regardless of Pr, and they penetrated the opposing boundary layer about 1–2 in. For the less viscous fluids, two dominant flow streams would develop thus imparting a higher degree of order to these flows. Photographs of these effects can be found in Fig. 8 (a, b and d).

With still larger inclinations the two dominant streams cut further into their opposing boundary layer flows so that at $\theta = 12°$ and 18° a continuous loop flow existed as shown in Fig. 8 (c, e and f) and in Fig. 9 except occasionally for a

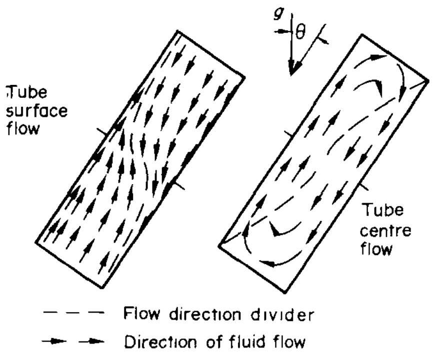

FIG. 9. Flow patterns in the inclined closed thermosyphon.

thin wedge of counter flow near a tube end which was actually a remnant of the original opposing boundary layer. This wedge would disappear for certain cases of extreme inclination or temperature difference or low viscosity and was a negligible portion of the flow even when present (for $\theta = 12°$ or 18°). At 18° the mass flow rates in the tube appeared to have increased by an order of magnitude over the corresponding perpendicular case. Certain regions of limited churning existed at the tube ends where the flow streams collided into the ends and at the tube middle where about two thirds of the wall flow from a given tube half would neck down to form the single stream (about one third of the opposing wall flow, see Fig. 9) that would rise (or fall) through the opposing tube half. These effects varied appreciably from case to case and are discussed further now.

For small angles ($\theta = 6°$ in particular) at $\Delta T = 3°$ the pattern described earlier was observed to form for all fluids but with some occasional unsteadiness for the 35% glycerin/65% water and distilled water cases, caused by the opposing forces exerted by the boundary layer and flow stream. The basic pattern was, however, still maintained. In all cases a vortex was observed in the tube middle (see dye trace photos, Fig. 8b) which generally presented minimal interference. However, for the nine degree temperature difference cases with 35% glycerin/65% water and distilled water, serious interference was found between $\theta = 6°$ and $\theta = 12°$. In these cases the two prevalent flow streams were actually intermittent or spurting. This was caused by a cyclic process which apparently was started and perpetuated by core vortex interference. This interference would cause temporary reductions in the flow rate through the two flow streams which was quickly augmented by increased growth of the opposing boundary layer wedge thus enhancing the flow reduction. With decreased flow, however, the dominant boundary layers experienced increased thermal gradients and hence increased buoyancy forces which were soon large enough to overcome the factors causing flow reduction, one of which (the vortex interference) also tended to abate simply as the flow rates decreased. When the tube inclination was increased to $\theta = 18°$ this phenomenon ceased and vortex interference was again slight (Fig. 8e).

Martin and Lockwood [11] observed similar flow patterns in the inclined open thermosyphon. They found that the fluid entered the thermosyphon at the (lower) trailing edge, went to the bottom, then rose along the (upper) leading edge. They found a steady improvement in stability over the vertical case as the inlet mixing was reduced or eliminated with increased tilting.

4.2 *Measured heat-transfer results*

The heat transfer measurements shown in Fig. 10 follow quite well what would be anticipated based on the observed flow patterns although the region where vortex interference was found might have been expected to correspond to decreased heat transfer. Also, the results follow the same trend as observed in the open thermosyphon [14, 15] (see [9] for a numerical comparison between these cases). The open thermosyphon results [14] for ethylene glycol showed,

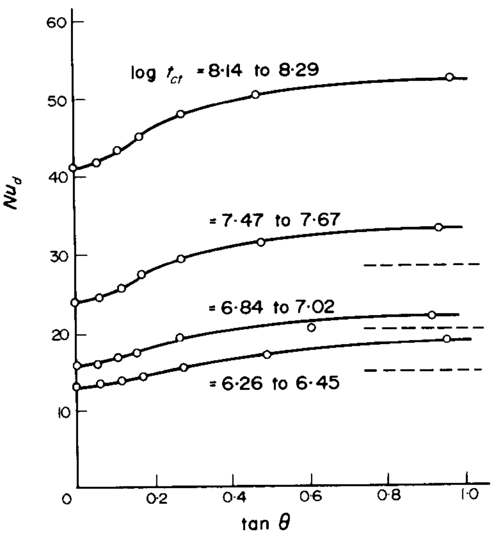

FIG. 10. Heat-transfer rates in the inclined closed thermosyphon with water.

however, an initial decrease for increasing θ and then a subsequent reversal in trend giving a definite rise. Based on the observations for the water/glycerin solution, this might be expected in the closed thermosyphon as well but probably at lower Pr since the vortex interference was not observed for ethylene glycol. The measured temperature distributions were in complete agreement with the flow process observed.

5. PREDICTION MODELS FOR HEAT TRANSFER IN THE CLOSED THERMOSYPHON

5.1 *Development of prediction models*

The problem of analyzing heat-transfer rates in the closed thermosyphon can be greatly simplified by seeking a method of joining two open thermosyphons, as opposed to solving the governing flow equations for the entire tube region. The experimental results of the previous sections strongly suggest that this is a valid approach. The fundamental objective of any joining model is to obtain a centerline temperature profile for the closed thermosyphon which is then sufficient to determine the heat-transfer rate using results from the open thermosyphon studies [7, 12, 13]. Since the assumption of a constant core temperature in each half of the vertical closed thermosyphon (with adiabatic ends) has been experimentally shown to be reasonable for boundary-layer flow, this modeling problem reduces to the determination of two temperatures, one for the lower core, $T_{0,1}$, and one for the upper core, $T_{0,2}$. Hence two governing equations are necessary. For cases with isothermal end conditions the same approach can apparently be followed since the centerline temperature profile is rather constant throughout either half. Due account, though, has to be taken of the effects of this base condition on the overall open system behavior as discussed before.

The first equation is obtained from an overall energy balance while the second equation is obtained from a local energy balance. It was observed that the value for T_{mix}, a single temperature for the thermosyphon core under pure mixing conditions which is determined from the overall energy balance (below), was generally quite close to the average of the calculated values of $T_{0,1}$ and $T_{0,2}$ for the data from Lock (section 3.3). Thus the first step of this convection model is to determine T_{mix} and then alter it so as to get the convective profiles $T_{0,1} = T_{mix} - \sigma$ and $T_{0,2} = T_{mix} + \sigma$ where σ is calculated from the local energy balance.

Since the heat flow into the closed thermosyphon must equal the heat flow out, $\dot{Q}_1 = \dot{Q}_2$. This relation can be expressed in terms of the Nusselt number and related parameters, as follows:

$$L_1 \Delta T_1 k_1 Nu_1 = L_2 \Delta T_2 k_2 Nu_2$$

where $\Delta T_1 = T_{1,1} - T_{0,1}$ and $\Delta T_2 = T_{0,2} - T_{1,2}$. Non-dimensionalizing the last equation using special variables for certain property groupings this equation becomes,

$$t_{ot,1}Nu_1 = \frac{A_{1,2}A_{2,2}^2a_1^2}{A_{1,1}A_{2,1}^2a_2^2}t_{ot,2}Nu_2$$

where

$$A_1 = \frac{v\alpha k}{\beta g} \quad \text{and} \quad A_2 = \frac{L}{a}.$$

Using the tabulated results from [1], this equation becomes,

$$\frac{t_{ot,1}}{t_{ot,2}} = \left[\frac{A_{1,2}A_{2,2}^2a_1^2}{A_{1,1}A_{2,1}^2a_2^2}\right]^{1/M_1} 10^{(b_{1,2}-b_{1,1})/M_1}. \tag{1}$$

Solving now for $T_{mix} = T_{0,1} = T_{0,2}$

$$T_{mix} = \frac{T_{1,1} + \chi T_{1,2}}{1+\chi} \tag{2}$$

where χ and A_3 are given by

$$\chi = \frac{A_{3,2}}{A_{3,1}}\left[\frac{A_{1,2}A_{2,2}^2a_1^2}{A_{1,1}A_{2,1}^2a_2^2}\right]^{1/M_1} 10^{(b_{1,2}-b_{1,1})/M_1} \tag{3}$$

$$A_3 = \beta g a^4/v\alpha L.$$

These equations for T_{mix} and $Nu_a \propto t_{ot}$ define a simple mixing mechanism model.

Before presenting the second equation, it may further be observed (Fig. 11) that heat-transfer rates based on $T_{1,1} - T_{0,1} = T_{1,1} - T_{mix}$ showed excellent agreement with experimental results for the 5 per cent mixing cases, i.e. those cases where the difference in centerline temperatures was less than 5 per cent of the overall temperature difference and hence these data were quite close to truly mixing data. In fact, the amount of error (albeit limited) in these particular calculations is directly proportional to the amount by which the T_0 actually deviates from the uniform value, T_{mix}. Thus the average error in heat transfer rates was about 3 per cent as compared with 23 per cent when using Lock's method that is sensitive only to property conditions in the bottom tube half.

To obtain σ, the second parameter for the convection model, a simple local energy balance in the exchange region is used. Thus,

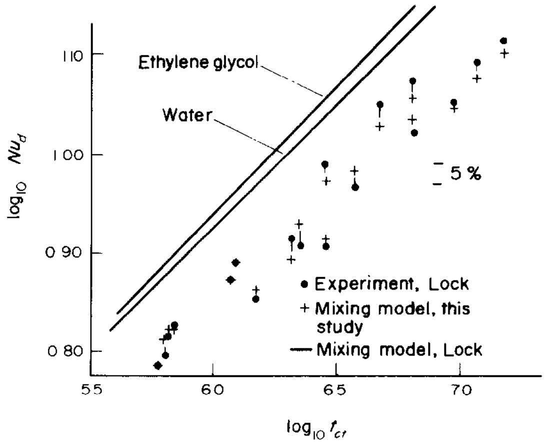

FIG. 11. Comparison of mixing models with basic mixing data.

Thermal energy core 2

$\propto$ Thermal energy boundary layer 1

$$\dot{M}_2C_{p_2}(T_{0,2} - T_{ref}) = \xi\dot{M}_1C_{p_1}(T_{mc,1} - T_{ref})$$

or non-dimensionally with $T_{ref} = T_{0,1}$,

$$\dot{m}_2A_{1,2}A_{2,2}^2A_{3,2}\frac{1}{a_2^2}2\sigma = \xi\dot{m}_1A_{1,1}A_{2,1}^2 \times \frac{1}{a_1^2}(t_{mc,1} - t_{0,1})$$

where $T_{0,1} = T_{mix} - \sigma$ and $T_{0,2} = T_{mix} + \sigma$ and ξ is a fraction which characterizes all losses due to conduction and mixing (and can be negative). Again using the results from [1], this gives

$$\sigma = \xi\frac{A_{1,1}A_{2,1}^2a_2^2}{2A_{3,2}A_{1,2}A_{2,2}^2a_1^2} \times \left(\frac{t_{ot,1}}{t_{ot,2}}\right)^{M_2}(t_{ot,1})^{M_3}\,10^{b_{2,1}-b_{2,2}+b_{3,1}} \tag{4}$$

where the t_{ot}'s are to be evaluated using T_{mix}. The two equations for T_{mix} and σ now define the simple convection model which is inherently an approximate one. Clearly, it presupposes (1) that T_{mix} is close to the average of $T_{0,1}$ and $T_{0,2}$ and (2) that in determining σ the new temperature profile obtained will not drastically alter the overall energy balance from which T_{mix} was obtained. Hence the simplified convection model is actually a blend between pure mixing and pure convection models. The determination of ξ is relatively easy after a few comparisons with data have been made.

For turbulent flow this general approach is not possible since reliable values for t_{mc} and $\dot{m}$ are not available, although [16] was considered for possible application. Thus only Martin's results for turbulent flow, for the low L/a ratio which is appropriate, can be used to give a mixing model:

$$Nu_a = 0{\cdot}10\, Ra_a^{\frac{1}{3}}.$$

For the general convection model, one must first calculate T_{mix}, using equations (2) and (3) and then σ, using (4), to get the value for $T_{0,1}$. With this value, t_{ot} based on $T_{1,1} - T_{0,1}$ can be found and then the open thermosyphon results give the heat transfer rate [1]. For the mixing (only) case, this can be expressed in a simple equation:

$$Nu_d = 0{\cdot}973\, 10^{b_{1,1}} \left[\frac{\chi}{1+\chi}\right]^{1\cdot 26} [t_{ct}]^{0\cdot 26} \qquad (5)$$

for the laminar mixing case with $Pr \geqslant 1$. A similar expression can be obtained for the turbulent case but the relation $Nu_a = 0{\cdot}196\, t_{ot}^{\frac{1}{3}}$ was found to work better than Martin's relation (they are equal at $L/a = 7{\cdot}5$). Thus,

$$Nu_d = 0{\cdot}191 \left[\frac{\chi}{1+\chi}\right]^{1\cdot 33} [t_{ct}]^{0\cdot 33}. \qquad (6)$$

This relation was reformulated from Martin's open thermosyphon equation, which was correlated for water and ethylene glycol in tubes for $L/a \leqslant 15$, with special attention to conditions in the closed system (further details are given in comparison section 5.2). It has been compared with closed thermosyphon results for two water cases.

In addition, another model can be developed that serves to estimate upper limits under certain conditions. This model is a pure convection model which presupposes the core temperature in one half of the thermosyphon to be equal to the mixing cup temperature of the boundary layer in the opposite half. Normally, however, such a model is inaccurate, but in the case of the inclined thermosyphon where very strong convective streams develop (indeed for large angles of inclination, θ, the boundary layer after contracting flows directly across at one place) this extreme might be considered for modeling the strongly inclined closed system even though deviations from a simple cylindrical boundary layer flow have occurred.

Using only the (laminar) results for the mixing cup temperature, and the requirement that $T_{0,1} = T_{mc,2}$ and $T_{0,2} = T_{mc,1}$ the following expression is obtained:

$$Nu_d \simeq 0{\cdot}973\, 10^{b_{1,1}} \left[\frac{1}{1+C}\right]^{1\cdot 26} [t_{ct}]^{0\cdot 26} \qquad (7)$$

where $C = 10^{b_{3,1}}(10^{-b_{3,2}} - 1)$. As indicated before, these models will not give a unique curve when plotted with Nu_d vs. t_{ct} due to the property dependence on $T_{1,2}$.

5.2 *Comparison with experimental data*

(a) *Laminar cases.* Figure 6 shows a typical comparison between the simplified convection model (using σ) and experimental results with ethylene glycol as the test fluid for $L/a = 22{\cdot}5$. Included are the predictions from an earlier model which lumped all fluid properties at a lower wall temperature. Values of ξ of about 0·6 or 0·7 were found to yield very good agreement for the shorter tubes, $L/a = 7{\cdot}5$ and 15 (not shown). The value, ξ, was found to drop to about 0·3 for the longest tube, $L/a = 22{\cdot}5$, and thus the effect of constriction has caused a change from nominally convective towards the mixing behavior.

As anticipated, the effect of viscosity on the convective structure is clearly evident in this analytical comparison. For water a low value of $\xi = 0{\cdot}3$ was found to be best for $L/a = 7{\cdot}5$ and ξ dropped to zero for $L/a = 15{\cdot}0$ thus becoming pure mixing, as shown in Fig. 5 (Lock's data). Thus the constriction effect is again apparent but it is, so far as the present data reveal, a uniform effect which shifts the entire heat-transfer curve as opposed to leveling off as in the case with impeded flow in the open thermosyphon. In fact, this constriction effect appears quite strong for $L/a = 15{\cdot}0$ for which much data falls below the $\xi = 0$ line and thus a significant amount of fluid in each boundary layer is, presumably, being turned back into its own core without ever crossing the tube mid-plane and completing the overall energy transfer process. For larger L/a ratios this constriction might give over to impedance with the resultant flattening out of the log Nu_a vs. log t_{ct} curve.

These values just quoted for ξ are based on comparison with Lock's data which had a nearly isothermal base. For the adiabatic base data from this study with $L/a = 8{\cdot}0$, a value of $\xi = 0{\cdot}7$ was found to be best as compared with 0·3 before.

(b) *Turbulent cases.* The turbulent analysis based on Martin's relation, $Nu_a = 0{\cdot}10 Ra_a^{\frac{1}{3}}$, was found to work quite well for $L/a = 7{\cdot}5$ (with water) but to fail for $L/a = 15$. Thus the effect of constriction (which causes core-boundary layer mixing) was again apparent. Since the laminar heat-transfer results with t_{ct} as a parameter instead of Ra followed the data quite well for all L/a values, Martin's expression was reformulated in terms of t_{ot} with L/a fixed at 7·5 as a reference case. Thus the resulting $Nu_a = 0{\cdot}196\, t_{ot}^{\frac{1}{3}}$ is tentatively suggested. Figure 5 shows that this equation is encouraging. Finally, in spite of the presence of some constriction effects, as discussed in part (a) above, it is clear that high heat-transfer rates are present which correspond to turbulent boundary-layer predictions.

(c) *Inclined cases.* It appears unlikely that any simple analysis could be formulated for the inclined case but naturally the previous simplified convection model (using σ) can be used at the one extreme where $\theta = 0$. For θ approaching 45°, the rates level out as would be expected based on the nature of the new flow pattern which is formed. In this case the upper limit might be expected to follow the ideal of the pure convection model, though of course not exactly. This however can only be calculated, presently, under laminar conditions and the experimental results of course include both laminar and turbulent cases (transition at about log $t_{ct} = 7{\cdot}6$). The results of the pure convection model are shown in Fig. 10 for three cases as dashed lines. The improved heat transfer of the system exceeds that which one would obtain by pure convection. This is consistent with the flow observations where very significant improvement in circulation was found.

The good results which equations (3)–(6) have so far given may be attributed to improvements in three areas: First, the boundary layer problem was reformulated so that a cubic temperature profile and $\beta \neq \delta$ gave better results for the open thermosyphon (see Fig. 4 of [1]). Second, different property references were used to model the property dependence for each half of the tube and the importance of this is evident in Fig. 11. Third, the nature of the joining technique, i.e. the usage of the overall and local (with ξ) energy balances, also leads to significant improvements as Figs. 5 and 6 illustrate. The extent of the improvement in joining technique might well be characterized by the role which the convection effectiveness parameter, ξ, plays. In actual practice equations (3)–(6) will be found to be easier to use than might be apparent due to the elimination of certain fixed geometry terms and certain slowly varying ordinate intercept values, b_i, from these equations.

For practical engineering applications these models should be helpful for predicting accurate heat-transfer rates in many cases and at least sensible trends in others. The values and trends given for ξ should serve as an adequate guide for the applied engineer to choose a value of ξ for applications when using fluids with $Pr > 1$ and $0 < L/a < 30$ and with either adiabatic or isothermal conditions.

5.3 *Geometry variations: The semi-closed thermosyphon*

This name was originated by Ogale [2] to describe the type of closed thermosyphon which he employed in order to increase the area available for heat transfer when it is necessary to reduce the length of the cooling section, such as is found in the turbine blade cooling problem. (Actually, Ogale's cooling section was eliptical in cross section with a hydraulic diameter of 2 a_2 in conjunction with a circular heating section.) It can be considered to be simply a closed thermosyphon where $a_2 > a_1$. In the same sense, of course, the open system can be considered to be a special case of the closed system where $a_2 \to \infty$ (ideally).

The preceding sections might be helpful in predicting heat transfer results for this case, and thus the previous models were formulated for arbitrary L/a ratios and values of a for each tube half. For unequal tube lengths, $L_1 \neq L_2$, these models should perform well as indeed was found with similar models [4, 8], within their general range of accuracy. For unequal radii, $a_1 \neq a_2$, however, the previous results may not be applicable since a basic change in flow pattern could exist: the presence of secondary vortices is now possible in the larger radii end.

For small changes in radii so that $a_1 \simeq a_2$ it may be expected that the system still functions very much like a regular closed thermosyphon but not if $a_2 \gg a_1$. In fact, by using the knowledge of flow patterns given in this study, the possible existence of a ring shaped vortex in the top end, for a vertical closed thermosyphon with $a_2 \gg a_1$, can be argued particularly for high Prandtl numbers or low temperature differences. If, however, the case with inclination is considered (or coriolis acceleration) such a ring vortex would become impossible for large inclinations, θ, (a small vortex could be left along the leading edge in the top half). In either case, the large number of corners which the flow path would have to follow would probably leave only very mixed conditions in the top half of the thermosyphon, especially for low Pr and/or high ΔT. Thus the system would behave very much like an open thermosyphon with extensive inlet turbulence.

Ogale's heat-transfer rates for NaK in a rotating apparatus are included in Fig. 3 of [1], and a comparison with the vertical liquid metal results is interesting. Considering the small tube diameter and the low Prandtl number of NaK ($Pr = 0{\cdot}005$), the results are in plausible relation to the rates for open thermosyphon behaviour. This is at least consistent with the type of flow mechanisms just postulated. Clearly, however, additional research into this problem is necessary.

6. SUMMARY

The flow process in either half of the closed thermosyphon has been shown to be very similar to that in an open thermosyphon. The exchange region shows some resemblance to the flow patterns around the orifice in an open thermosyphon but it is considerably more stable. This exchange process is convective for low temperature diferences and/or high Prandtl numbers and changes to a mixing process as ΔT increases or Pr decreases. The change-over is, as a rule, rather complete at the condition of transition to turbulence.

A fundamental consequence of the difference in orifice and exchange region stability in the open and closed systems, respectively, is that turbulent boundary layer flow with increasing heat transfer was found in the closed thermosyphon under conditions which caused an impeded turbulent flow with reduced heat transfer in the open thermosyphon.

The effect of inclination is to develop a loop flow up the leading edge and down the trailing edge of the thermosyphon with consequent heat-transfer improvements.

Under all conditions the fluid properties, particularly the Prandtl number, play a significant role. Aside from fixing the conditions of stability, they are also extremely important for correct modeling of the heat-transfer processes and it was found that such models must employ the property values at both the high and low wall temperatures. Contrary to [4], it was found that there is no reason to expect an optimal Prandtl number for boundary layer heat-transfer processes.

A convective exchange model was formulated which shows good agreement with six experimental cases using two fluids and three length to radius values.

Further work is necessary for liquid metals and thermosyphons with different radii for each tube half. This case has possibilities for turbine blade cooling and the results so far available resemble open thermosyphon behavior.

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Note: References 7 and 9 are obtainable from University Microfilm, Inc., Ann Arbor, Michigan, U.S.A.

PROCESSUS DE TRANSPORT MONOPHASIQUE DANS UN THERMOSYPHON FERMÉ

Résumé—Les résultats de deux études expérimentales avec visualisation de l'écoulement et mesures du transfert thermique sont présentés pour des liquides ordinaires dans des dispositions verticales et inclinées. On trouve que le procédé d'échange au milieu du tube, à la confluence de la couche limite s'élevant à partir de l'extrèmité chauffée et de la couche limite descendant depuis l'extrèmité refroidie, est fondamentalement convectif par nature, la conduction et le mélange jouant des rôles auxiliaires importants. L'accroissement de la différence de température globale ou la diminution du nombre de Prandtl entraine l'accroissement de l'importance du mélange jusqu'à ce que celui-ci prédomine. Sous des conditions pour lesquelles un écoulement induit dans un thermosyphon ouvert est obtenu, on trouve que l'écoulement à la couche limite est maintenu dans le thermosyphon clos, permettant ainsi un rendement global du thermosyphon clos proche de celui du termosyphon ouvert. Il a été trouvé que l'inclinaison accroît le mode d'echange convectif, avec une circulation fermée complète pour des angles modérés, causant par ce moyen un transfert thermique accru. On donne des méthodes de prédiction précises pour un comportement vertical et des tendances pour un comportement incliné. On considère le système semi-fermé utilisé récemment (par Ogale, Delft) dans un modèle d'ailette de turbine.

EINPHASIGE TRANSPORTVORGÄNGE IM GESCHLOSSENEN THERMOSYPHON

Zusammenfassung—Die Ergebnisse zweier experimenteller Untersuchungen mit Sichtbarmachung der Strömung und Wärmeübergangsmessungen werden für gewöhnliche Flüssigkeiten unter senkrechten und geneigten Bedingungen angegeben. Der Austauschvorgang in der Rohrmitte, wo die vom beheizten Ende aufsteigende und die vom gekühlten Ende herabfallende Grenzschicht zusammentrifft, ist grundsätzlich konvektiver Natur, wobei Leitung und Mischung wichtige Sekundärrollen spielen. Erhöht man die Gesamttemperaturdifferenz oder verkleinert man die Prandtl-Zahl, steigt der Einfluss des Mischvorgangs, bis er vorherrscht. Unter Bedingungen, für die man beim offenen Thermosyphon behinderte Strömung erhält, bleibt beim geschlossenen Thermosyphon die Grenzschichtströmung bestehen. So ist es möglich, den Gesamtwirkungsgrad des geschlossenen Thermosyphons dem des offenen anzunähern. Ein Kippen des Thermosyphons bewirkteine Erhöhung des konvektiven Austausches, wobei sich bei mässigen Kippwinkeln eine vollständige Zirkulationsschleife einstellt, die eine Erhöhung des Wärmeübergangs bewirkt. Methoden zur exakten Voraussage des vertikalen Verhaltens und zur Bestimmung der Tendenz für den geneigten Fall werden angegeben. Über das halbgeschlossene System, wie es kürzlich (von Ogale und Delft) in einem rotierenden Turbinenschaufelmodell verwendet wurde, wird kurz berichtet.

ОДНОФАЗНЫЕ ПРОЦЕССЫ ПЕРЕНОСА В ЗАКРЫТОМ ТЕРМОСИФОНЕ

Аннотация—Представлены результаты экспериментального исследования по визуализации потока и измерению теплообмена в обычных жидкостях при вертикальном и наклонном положениях объекта. Обнаружено, что в средней части трубы, в точке смыкания встречных пограничных слоев, развивающихся от нагретого и холодного концов, процесс теплообмена является преимущественно конвективным, а теплопроводность и перемешивание играют второстепенную роль. Эффект возрастания общего температурного перепада или уменьшения числа Прандтля должен увеличивать долю перемешивания до тех пор, пока оно не начинает играть превалирующую роль. Обнаружено, что в закрытом термосифоне при условиях, вызывающих торможение движения в открытом термосифоне, имеется течение в пограничном слое. Это позволяет получить к.п.д. закрытого термосифона такой же, как у открытого. Найдено, что при средних углах наклон интенсифицирует конвективный теплообмен с циркуляционным контуром. Приводятся точные методы расчета для режимов, имеющих место при вертикальном и наклонном положениях устройства. Рассматривается полузамкнутая система, использованная недавно Огалем, Делфтом при моделировании вращающегося диска турбинных лопаток.