Advances in

HEAT TRANSFER

Thomas F. Irvine, Jr.

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Volume 9

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PREFACE

The serial publication "Advances in Heat Transfer" is designed to fill the information gap between the regularly scheduled journals and university level textbooks. The general purpose of this series is to present review articles or monographs on special topics of current interest. Each article starts from widely understood principles and in a logical fashion brings the reader up to the forefront of the topic. The favorable response to the volumes published to date by the international scientific and engineering community is an indication of how successful our authors have been in fulfilling this purpose.

The editors are pleased to announce the publication of Volume 9 and wish to express their appreciation to the current authors who have so effectively maintained the spirit of the series.

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C. L. TIEN AND G. R. CUNNINGTON

Advances in Thermosyphon Technology[†]

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[†] This work was initiated while the author was an NDEA Title IV Graduate Fellow at Purdue University, continued while conducting postgraduate research at the Technische Hochschule, Aachen, W. Germany as an NSF Postgraduate Fellow and concluded while working as an Assistant Project Engineer, Pratt & Whitney Aircraft, East Hartford, Connecticut.

I. Introduction

A. CLASSIFICATION AND APPLICATION OF THERMOSYPHON SYSTEMS

A thermosyphon[1] is a circulating fluid system whose motion is caused by density differences in a body force field which result from heat transfer. Mechanical inputs have so far been excluded from all thermosyphon studies. Davies and Morris (*24*) have suggested that thermosyphons can be categorized according to (a) the nature of boundaries (is the system open or closed to mass flow?), (b) the regime of heat transfer (is the process purely natural convection or is it mixed natural and forced[2] convection?), (c) the number or type of phases present (is the system in a single- or two-phase state?) and (d) the nature of the body force (is it gravitational or rotational?)

Unfortunately a definition as broad as the one given above would require the preparation of a book, not a review article, to do it justice. In fact, the above definition, suggested by Davies and Morris in 1965, is so broad as to include all natural convection processes, plus others, and thus it is well to note that all systems to which the name *thermosyphon* has been applied in formal studies (except the discussion by Davies and Morris (*24*)) are in fact systems which have the intrinsic function of removing heat from a prescribed source and transporting heat and mass over a specific path (frequently a recirculating flow) and rejecting the heat and or mass to a prescribed sink. That is, the path of the *circulating* flow which transports the thermal energy is or can be totally *prescribed.* Thus, for example, while ordinary free convection from plates and cylinders may tacitly meet these criteria, they generally are of interest only from the standpoint of rejecting heat and the subsequent transporting is of secondary or of little interest. Indeed, in industrial applications the path of heat flow in such a free convection process is rarely *prescribed* and will vary considerably. Furthermore, thermosyphon flows are intrinsically driven by thermal *buoyancy forces*, either locally or in an overall sense. A simple loop flow may well be the result of local buoyancy forces alone, but a multibranched flow circuit can easily incorporate sections in which the flow direction is contrary to the local buoyancy force resulting from pressures created by the overall system buoyancy forces. Based on these factors, the following definition will be used in

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[1] **The origin of the name "thermosyphon" is uncertain; however, the name appeared as early as 1928 in the sales literature of Deere and Co. to aptly describe their cooling system.**

[2] **Mixed convection requires a dividing partition across which pressure differences can be established.**

this review (roughly following the definition used also by Lock (*82*)): A *thermosyphon* is a *prescribed circulating* fluid system driven by thermal *buoyancy forces*. This definition includes *all* basic studies to which the name thermosyphon has been applied in the literature (with the exception of parts of Davies and Morris (*24*), which is not a study of any particular system but rather a general discussion) and clearly defines a class of thermal systems which have become industrially important. The preceeding distinction notwithstanding, Davies' subcategories are still very convenient and will be used.

The most common industrial thermosyphon applications include gas turbine blade cooling (*3*, *9*, *14*, *20–22*, *27*, *33*, *36*, *37*, *39–42*, *44*, *54*, *65*, *67*, *93*, *97*, *98*, *101*, *107*, *112*, *113*), electrical machine rotor cooling (*25*, *38*, *95*, *96*), transformer cooling (*68*, *71*), nuclear reactor cooling (*23*, *48*, *92*, *114*), heat exchanger fins (*73*, *74*, *85*), cryogenic cool-down apparatus (*10*, *11*, *43*, *69*), steam tubes for bakers' ovens (*94*), and cooling for internal combustion engines (*70*, *111*, *115*). Other intriguing thermosyphon (or very closely related) problems include the convection in the earth's mantle (*102*), the temperature distribution in earth drillings in steam power fields (*28*), plus the use of thermosyphons for the preservation of permafrost under buildings in the Canadian northland (*66*, *76*, *84*), and the maintenance of icefree navigation buoys (*74*). A variety of thermosyphon characteristics are responsible for the applications found to date and can lead to numerous future applications. For example, a thermosyphon can behave as a thermal conductor with either a small or a large thermal impedence depending on system choice; it can be used as a thermal diode or rectifier (*43*, *74*); or even as a thermal triode (*43*), permitting a variation in heat flow based on small changes in temperature. Table I shows a large variety of thermosyphons which have been studied and/or are in use today. The application of thermosyphons to gas turbine blade coóling has clearly played a key role in thermosyphon research and will receive special attention later.

The first section of this review considers a common single-phase, natural-convection open system in the form of a tube open at the top and closed at the bottom; the second section considers a simple single-phase, natural-convection closed system in the form of a tube closed at both ends; the third section considers various single-phase, mixed-convection thermosyphons, so-called closed-loop thermosyphons; the fourth section reviews two-phase[3] and critical state thermosyphons and

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[3] A note about semantics is in order. These systems have occasionally been called "wickless heat pipes" which is unfortunate since a wick is an integral and important part of a heat pipe. Any such system without a wick should certainly be considered a two-phase thermosyphon.

TABLE I: CLASSIFICATION OF THERMOSYPHONS AND EXAMPLES OF THEIR APPLICATIONS[a]

Heat-transfer regime	Body force	Open systems		Closed systems	
		Single phase	Two phase	Single phase	Two phase
Free convection	Static	Hot springs Warming kettles	Washing machine boilers Kettles	Electric immersion domestic hot-water heaters Ovens Oil-filled electric convector heaters (internal)	Fire-tube boilers Hydrometeorology Baker's ovens Ice prevention system for navigation buoys Heat exchanger fins Cryogenic cool-down equipment
	Rotating	Axial-flow gas-turbine blade cooling	Axial-flow gas-turbine blade cooling	Axial-flow gas-turbine blade cooling	Axial-flow gas-turbine blade cooling Rotary condensers
Mixed convection	Static	Cooling of encased electrical equipment Fireplace and chimney	Steam fields	Gas-fired domestic hot-water heaters Gravity-flow central heating (internal) Transformer cooling (internal) Car-engine cooling (internal) Nuclear reactor cooling Heat exchanger fins	Water-tube boilers Hydrometeorology with water power Transformer cooling (internal) Coffee percolators Annular jet mercury vapor pumps
	Rotating			Axial and radial-flow gas-turbine blade cooling	Electrical-machine rotor cooling

[a] Adapted from Davies and Morris (*24*), according to the revised definition.

finally a review of the turbine blade cooling problem is given in the fifth section. It is hoped that the review of these systems, which includes all basic thermosyphon studies, will provide a background of information for related and new thermosyphon problems.

However, before examining these systems it is profitable to consider the matter of suitable property modeling in all thermosyphon problems.

B. PROPERTY MODELING FOR THERMOSYPHON SYSTEMS

With the exception of density, all thermosyphon analyses to date have assumed constant properties; hence it is quite important to make a wise choice of reference temperature; indeed, poor choices have led to very sizeable errors in calculating heat transfer. Table II shows a few property variation ratios which illustrate the nature of variations possible.

Table II shows clearly that the most important property variation for ordinary liquids is that of viscosity. Hence Lock (*82*) neglected all property variations except μ (and of course included $\rho(T)$) and found that the integral momentum and energy equations can be reduced directly [see Eq. (9)] to show that the wall temperature is the appropriate property reference temperature. This somewhat unusual reference temperature has fortunately been used in nearly every open thermosyphon study. It might also be mentioned that this choice is also the most practical since the use of, say, the core temperature, is often difficult to predict. In one case, Foster (*34*), the core temperatures were measured and a film temperature employed; regrettably this choice led to the conclusion or result that Nu decreased with increasing Pr, contrary to all other thermosyphon findings and general free-convection knowledge. In short, the use of the core temperature is undesirable; the wall temperature has proven most reliable.

For treating liquids in the closed thermosyphon, it has been shown by Japikse and Winter (*59, 60*) that the wall temperature in each tube half should be used to model the flow process in that tube half. This is of considerable importance because not only can heat transfer rates be in error by as much as 50% if only one reference temperature is employed, but it is occasionally impossible to recognize the mode of flow which exists if this rule is not employed (see Japikse (*62*) for a discussion of two such cases).

For gases, Table II shows that property variations do not appear to be too large; but they are sufficiently subtle to make up the difference. Consider for the moment the Gr number, now based on the film temperature for purposes of discussion:

$$\mathrm{Gr} = g\beta\,\Delta T a^3/\nu^2$$

TABLE II

VARIATION OF FLUID PROPERTIES

	Gases										
1 200°F 2 100°F 3 1500°F 4 1000°F	ρ_1/ρ_2	ρ_3/ρ_4	μ_1/μ_2	μ_3/μ_4	C_{p_1}/C_{p_2}	C_{p_3}/C_{p_4}	k_1/k_2	k_3/k_4	β_1/β_2	β_3/β_4	$\mathrm{Pr}_1/\mathrm{Pr}_2$	$\mathrm{Pr}_3/\mathrm{Pr}_4$
Air	0.85	0.75	1.33	1.22	1.00	1.05	1.13	1.25	0.85	0.75	1.0	1.04
H_2	0.86	0.74	1.12	1.22	1.01	1.03	1.11	1.25	0.85	0.75	0.99	1.01
H_2O (1 400°F 2 300°F)	0.88	0.75	1.13	1.29	1.01	1.09	1.17	1.47	0.90	0.75	0.99	0.96

	Liquids					
1 200°F 2 50°F	ρ_1/ρ_2	μ_1/μ_2	C_{p_1}/C_{p_2}	k_1/k_2	β_1/β_2	$\mathrm{Pr}_1/\mathrm{Pr}_2$
H_2O	0.96	0.23	1.0	1.19	8.16	0.20
Light Oil (2 60°F)	0.95	0.043	1.19	0.96	1.11	0.053
Glycerin (1 120°F)	0.98	0.048	1.11	0.98	1.28	0.052
Mercury	0.99	0.79	1.00	1.28	1.00	0.59