Heat Transfer Engineering, 33(15):1220–1231, 2012

ISSN: 0145-7632 print / 1521-0537 online
DOI: 10.1080/01457632.2012.692294

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heat in history

Heat Transfer Research in Sweden: Historical and Current Activities

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This article describes some historical and significant contributions in the field of heat transfer from various Swedish universities and researchers. It also gives an overview of what kind of heat transfer-related research has been going on recently, as well as some current activities. Traditionally, research projects have been associated with the Ph.D. education programs and in these, common theses for the licentiate of engineering and doctor of philosophy appear, besides publications in journals, conference proceedings, and technical reports. The only location with a Ph.D. program in heat transfer and the main research focus on this subject is at Lund University. Nevertheless, heat transfer research is carried out at various universities, but not as the major subject.

INTRODUCTION

In the past, most research works were carried out by individuals, and to a limited extent. Focus was mostly on fundamental issues. Publication was not always a priority. As the university education and research were extended and new universities were started, new research groups (professors, senior researchers, and Ph.D. students) were established as the available funding was increased. Also over the years, there has been a shift from fundamental research to applied and industry-oriented studies.

In this article some important contributions are highlighted and the most important researchers and departments are briefly introduced. The given references are just examples of publications. Figure 1 shows a map indicating the locations of the major universities in Sweden.

It should also be noted that computational fluid dynamics (CFD) for fluid flow, heat and mass transfer, combustion, and chemical processes has become an engineering tool, and nowadays several commercial codes are provided by competing companies, and for research and development (R&D) at universities both commercial codes and in-house codes are being used. Similarly experimental equipment has been developed significantly and tools like laser Doppler velocimetry (LDV), particle image velocimetry (PIV), liquid crystal thermography (LCT), and infrared thermography (IRT) have become easily available and appear in engineering and research work frequently. This also means that heat transfer issues or problems are also tackled by research groups not primarily focusing on heat transfer.

WORK BY NILS FRÖSSLING AT LUND UNIVERSITY, (LUND), KTH (STOCKHOLM), AND CHALMERS UNIVERSITY (GOTHENBURG)

Nils Frössling started his academic career at Lund University, Department of Physics. At first he carried out a theoretical and experimental investigation of evaporation of falling drops. The drops were placed on a thin glass rod or a thermocouple and a wind tunnel created a forced airflow that was coming from below. The evaporation was measured by photographing the drops repeatedly on an increased scale. The drop radius varied from 0.1 to 0.9 mm. The air velocity was 0.2–7 m/s and the corresponding Reynolds number was in the range of 2 to 800. The liquids used in the experiments were nitrobenzene, aniline, and water. Frössling also considered sublimation of naphthalene spheres in the same Reynolds number range and he presented distribution of the sublimation rate over the surface of the naphthalene spheres. Figures 2 and 3 show the experimental

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Figure 1 Map showing locations of major universities in Sweden. (Color figure available online.)

setup. This part of the work is frequently cited in the literature as the pioneering work using sublimation of naphthalene in mass transfer experiments and converting such data to heat transfer data (Nusselt numbers, Nu) using the heat and mass transfer analogy.

The results (actually mass transfer) were already correlated by a formula in 1938; see reference [1].

$$Sh = 2 + 0.55 \cdot (\mathrm{Re})^{0.5} \cdot (Sc)^{1/3} \tag{1}$$

Equation (1) with the constant 0.55 exchanged by 0.6 is more commonly referred to in the literature and then usually referenced to Ranz and Marshall [2], who also did corresponding experiments but later.

Later on, Frössling started to work on calculations of heat transfer and fluid flow in laminar boundary layers by using and further developing the method based on the Blasius series or generalized Blasius series solutions. He extended the series by introducing universal functions for axisymmetric flow and for temperature and concentration fields. He also showed that for similar velocity distributions outside the boundary layer, the $\mathrm{Nu}/\sqrt{Re}$ is only a function of the Pr number. Further details are available in references [3] and [4].

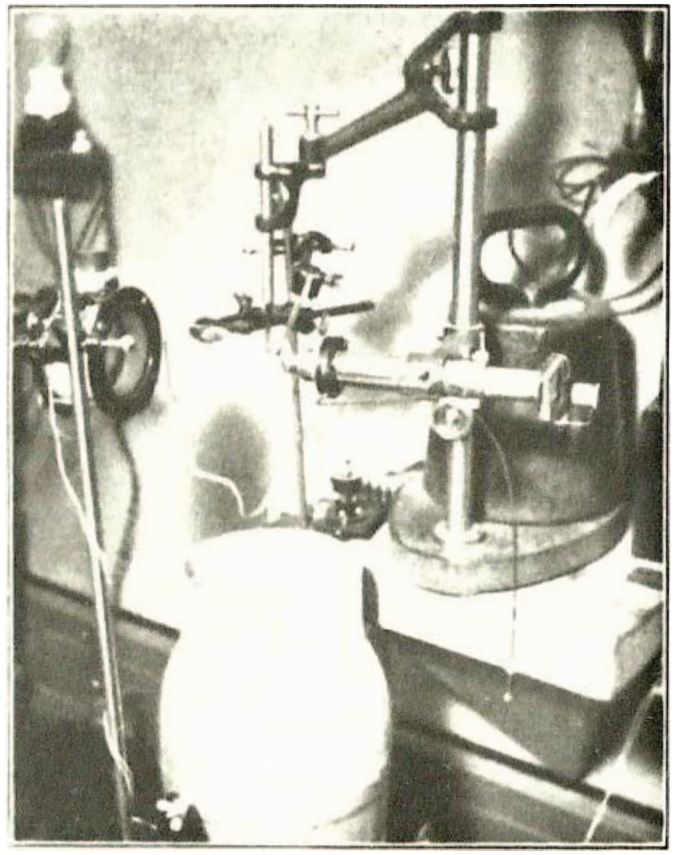

Figure 2 Frössling's experimental setup [1]. (Color figure available online.)

Frössling spent a short time period at KTH (Royal Institute of Technology) in Stockholm, but his major concern there seemed to be finalizing his Ph.D. thesis and achieving the honorary degree docent [5, 6].

As Frössling was appointed a professor in Applied Thermodynamics and Fluid Mechanics at Chalmers University of Technology in 1959, he with several co-workers continued his research on laminar boundary calculation methods. Extensions for the series solution method were exemplified by introducing a more general description of the velocity distribution outside the boundary layer. Later on, the thermal boundary condition of an isothermal wall surface was relaxed and nonisothermal surface temperature distributions were introduced. Then universal functions for the boundary layer temperature distribution were developed. This enabled studies with solid bodies having limited thermal conductivity, and the concept of conjugated heat transfer was introduced. Also, the shape of the immersed solid bodies was developed and some works considered so-called lenticular cylinders and wedge-shaped

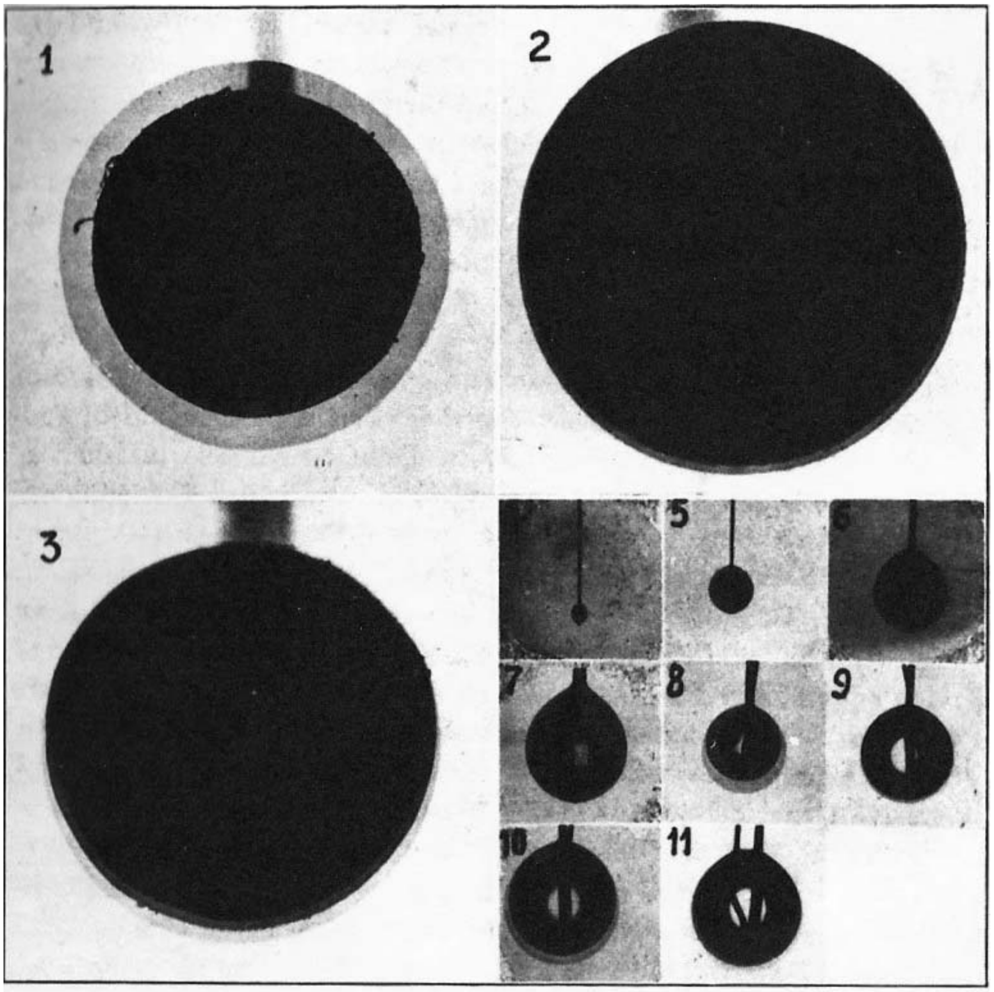

Fig. II. 1—3 Naphtalin; 4—7 Nitrobenzol; 8—11 Wasser.

Figure 3 Droplets in the experiments of Frössling [1].

bodies. Because of the limitations of series solutions like slow convergence at far distances from the starting position of the laminar boundary layer, Frössling also initiated application of finite-difference methods for the downstream boundary-layer calculations. Because of the parabolic nature of the boundary layer equations, these require initial data for the velocity and temperature fields. The series solutions were used to provide such data. A few references are [7–9].

Frössling also at Chalmers introduced studies on free-stream turbulence on boundary-layer heat transfer (on circular cylinders and flat surfaces), infrared technique to measure surface temperature, LDA measurements of fluid flow, and hot-wire anemometry for turbulent boundary-layer flow. He succeeded in building up a research laboratory of high quality and with modern equipment, including relatively big low-speed wind tunnels. Also the undergraduate education was developed to a high standard.

Joseph Kestin, a professor at Brown University, Providence, RI, met Frössling several times and Professor Kestin at some time suggested (it is not totally confirmed that it was Kestin being the originator) that Frössling numbers should be introduced as

$$Fr_1 = \frac{Nu - 2}{\mathrm{Re}^{0.5} \cdot \mathrm{Pr}^{1/3}} \tag{2}$$

and

$$Fr_2 = \frac{Nu}{\sqrt{\mathrm{Re}}} \tag{3}$$

The second one of these, Eq. (3), is more frequently used than Eq. (2).

Nils Frössling did not publish much in the open literature, and the work of his students was mainly published in several licentiate of engineering theses and a few Ph.D. theses. Nevertheless, several of his co-workers reached professorships at universities, and management and R&D top positions in companies.

Nils Frössling was born in 1913, retired in 1980, and passed away in 1986. He suffered from a stroke shortly after his retirement and was partly physically disabled during his last years. In younger days he was a competitive runner and won a Swedish championship in relay, 4 × 100 m. Figure 4 shows Frössling and the author around 1978 at a national Swedish conference.

CONTRIBUTION BY BO LECKNER, CHALMERS UNIVERSITY

Bo Leckner, now retired but still a part-time active professor in energy technology at Chalmers University, contributed in a specific area as he considered emissivities and absorptivities for combustion gases like water vapor and carbon dioxide. By his work the accuracy of the original charts and correlations presented by Hottel [10] was improved. Leckner's work [11] has been well recognized; see, for example, Modest [10].

Later on, Leckner and co-workers have also initiated and carried out applied research on fluidized-bed heat transfer as part of extensive research on various fluidized-bed combustion equipment. See also the description of the Department of Energy Conversion at Chalmers.

PROFESSOR BENGT SUNDÉN'S RESEARCH AT CHALMERS UNIVERSITY AND LUND UNIVERSITY

Professor Sundén started his research career in 1973 at Chalmers University of Technology with Frössling as supervisor, and then from 1992 he continued as a professor in heat transfer at Lund University. His first research activities concerned numerical investigation of fundamental aspects of freestream turbulence effects on tubes in cross flow and conjugated heat transfer problems for extended surfaces like fins and thick-walled cylindrical objects. The freestream turbulence studies included turbulence modeling, and he showed for the first time the importance of the turbulent length scale on local heat transfer. Previously only effects of the turbulence intensity were known in the literature. The studies on fins concerned laminar and turbulent boundary layer flow and heat conduction in the fins. Professor Sundén introduced a convection–conduction parameter (CCP) that can be used to evaluate whether a conjugate heat transfer analysis is needed or if an engineering analysis is sufficient. For the thick-walled cylindrical objects exposed to low-Reynolds-number cross-flow, the ratio of the thermal conductivities of the fluid and solid as well as the buoyancy parameter Gr/Re^2 were found to be important as the heat conduction

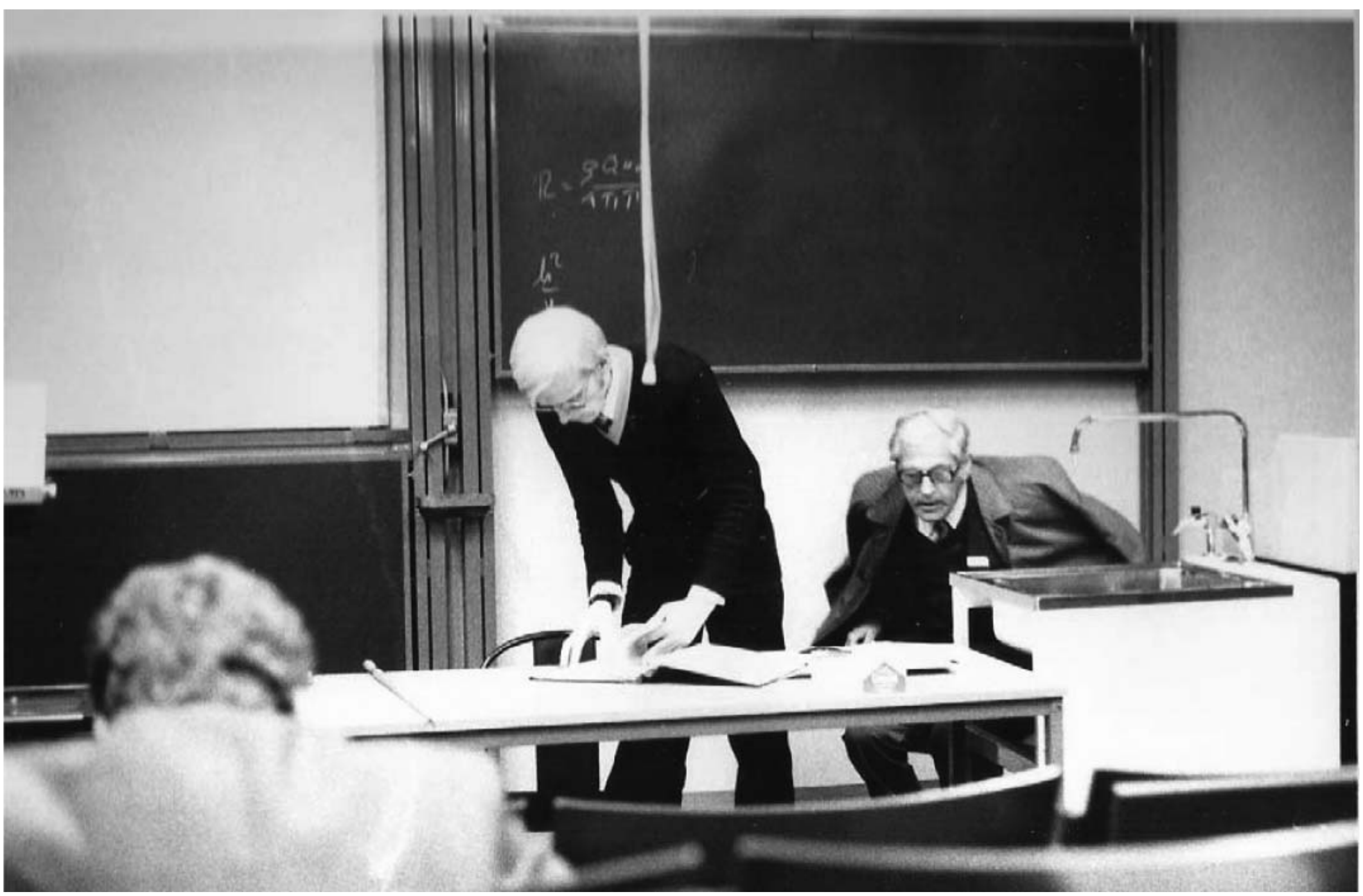

Figure 4 Frössling (to the right) and the author at a national Swedish conference in 1978.

became two-dimensional. Some references are represented by references [12–14].

Later on, convective heat transfer and fluid flow in ducts became a major topic. The cross-sectional shape of the ducts as well as surface modifications (e.g., ribs, dimples, inserts) for heat transfer enhancement were investigated thoroughly both experimentally and numerically. In the experimental work the liquid crystal technique was further developed and applied. LDV and PIV measurements were applied for detecting flow structures. The numerical investigations included to a large extent turbulence modeling, and Professor Sundén and co-workers evaluated several models and showed the limitations of such in complex flow fields and geometries. In addition, they found the influence of geometrical parameters for heat transfer and pressure drop in various duct flows. Based on the results, guidelines to balance heat transfer versus pressure drop were suggested. Applications for these studies were found in compact heat exchangers and gas turbine cooling (i.e., blades, guide vanes, and combustor walls). A current test rig for rectangular duct flows is illustrated in Figure 5. Some publications are represented by references [15–26].

Performance of plate heat exchangers (PHEs) as condensers and evaporators has been established experimentally. Correlations for condensation of steam and evaporation of ammonia have been found. For single-phase heat exchangers, computer codes for design and performance calculations have been developed. Also, the relevance and importance of maldistribution in PHEs have been investigated. For recuperators in gas turbine systems the research of Professor Sundén and co-workers recommended cross-corrugated surfaces for achieving compact units. Some references are exemplified by references [15, 27–35].

Heat exchanger design procedures have been further developed, and optimization has been considered, as well as enhanced heat transfer. For heat exchanger networks the pinch technology has been demonstrated and applied to several industrial case studies. Heat exchangers like radiators, rotary generators, plate heat exchangers, condensers, and evaporators have been considered. Micro heat exchangers have been in focus more recently. Current activities include foam heat exchangers and future vehicle heat exchangers.

Figure 5 A current multipurpose test rig for rectangular duct flows in the Heat Transfer Laboratory, Lund University. (Color figure available online.)

Thermal radiation with participating media has attracted Professor Sundén for research due to its significance in gas turbine combustors and in furnaces for biomass combustion, as well as in fires. The contributions mainly are in improving the engineering computation of thermal radiation in participating media. An important aspect is the estimation of the radiative properties of the participating media, that is, gases and particles. Much effort has been spent here, and the results show how the absorptivity, transmissivity, and scattering coefficients can be calculated in several cases. Solid fuels and various biofuels have been considered and the properties of some additional gases like CH_4 and CO have been evaluated. Overall, the prediction tool for calculating the heat load in furnaces and gas turbine combustors has been improved. CFD methods (including combustion modeling) have been linked with solution methods for the radiative transfer equation (RTE). Due to his experience in analysis and modeling, Professor Sundén has contributed in moving the frontier forward and improved engineering calculation methods. For further details, see references [36–38].

Heat transfer analysis in combustion engines has been linked to research on the knock phenomenon, ion current transport, and thermal radiation in diesel engines. In addition, studies to improve the performance in the cooling jacket have been included. The knock and ion current projects involved simulation of chemical kinetics besides the overall combustion process. Overall the intention is to contribute to improving the efficiency and reducing the emissions in combustion systems.

Over the past 15 years, Professor Sundén and his co-workers have also put research efforts into modeling aspects of transport phenomena, that is, mass, momentum, heat, chemical, and electrochemical reactions in fuel cells. This was started by considering the phenomena in the fuel and oxidant channels, and then the cathodes, catalytic layers, and electrolyte have been taken into account to model the whole units. Unit cells, stacks, and systems have been considered. Balance of power plants is another topic under consideration. Auxiliary equipment like heat exchangers has also been considered. Phenomena, characteristics, and influence of a variety of parameters have been revealed. Currently, modeling of multiscale and multiphysics transport phenomena (ranging from nanoscale up to macro levels) is under development. High-temperature solid oxide fuel cells (SOFC) and low-temperature proton exchange membrane fuel cells (PEMFC) are considered. The methods of analysis, as well as the results, have contributed to improving the basic understanding of fuel cells and development of guidelines for design. For further details, see references [39] and [40].

Currently, the main focus on gas turbine heat transfer is on the internal blade tip cooling and development of methods to enhance the tip cooling efficiently at low manufacturing costs and with limited pressure drop penalty. The most recent work on tip cooling of gas turbine blades have received good recognition [41–43].

Up to now, Professor Sundén has supervised 34 Ph.D. theses, 40 licentiates of engineering theses, and about 170 M.Sc. theses.

CONTRIBUTIONS FROM CHALMERS UNIVERSITY

At this university most heat transfer-related research has been carried out at the previous Department of Applied Thermodynamics and Fluid Mechanics (TFD) (described under Frössling and Sundén), Division of Energy Conversion, and Division of Heat and Power Technology. The TFD has now been split up and is included in the Department of Applied Mechanics. The research profile includes combustion, fluid mechanics, and vehicle engineering.

Division of Energy Conversion at Department of Energy and Environment, Chalmers

For several years, experimental and theoretical/numerical heat transfer investigations have been part of the extensive research on combustion of coal and biomass in stationary-bed boilers, atmospheric fluidized-bed boilers, and circulating fluidized-bed boilers. Some heat transfer works have been related to biofuel combustion, and lately investigations related to capturing and sequestration of CO_2 and oxyfuel combustion have been carried out.

Overall the research covers the broad areas like energy conversion, sustainable energy systems, and energy systems technology. However, the main focus is on combustion and its environmental impact, separation of CO_2 in combustion processes, and issues on energy systems.

Current leaders are Professors Filip Johnsson and Anders Lyngfelt (former students and now successors of B. Leckner). References [44–49] exemplify some contributions.

Division of Heat and Power Technology, Chalmers

The overall research concern is to disseminate knowledge about efficient energy usage and reduction of CO_2 emissions in industries.

The research includes components in industrial energy systems and system studies concerning technology, economy, and the environment. The components of interest are heat exchangers, heat pumps, heat, and power, as well as industrial separation processes. Process integration with target to reduce energy consumption is a major concern.

Some heat transfer-related activities are exemplified by falling film evaporation related to the pulp and paper industry, and evaporation and heat exchangers in heat pump applications.

Current leaders are Professors Thore Berntsson and Lennart Vamling. Publications from this division are exemplified by references [50–58].

An early work with relevance for plate heat exchangers was the Ph.D. work by Dr A. Kullendorff. The paper by Rosenblad (precessor of Berntsson) and Kullendorff [59] has found some significance and recognition for R&D work on plate heat exchangers.

CONTRIBUTIONS FROM ROYAL INSTITUTE OF TECHNOLOGY (KTH), STOCKHOLM

At this university most heat transfer-related research has been carried out at the division of Nuclear Reactor Technology, the division of Applied Thermodynamics and Refrigeration, and the Nuclear Safety Division.

Nuclear Technology Division

The research activities at this division have traditionally included two-phase thermal hydraulics in fuel assembly geometries, reactor safety, plant instrumentation, and severe accidents. The current activities concern computational methods, heat transfer, transport phenomena, reactor technology, and advanced nuclear power systems.

The division possesses a high-bay laboratory, which includes a high-pressure, 1-MW heated water loop for two-phase flow studies and dry-out testing. Circumferentially nonuniform heating can also be studied. These activities were started by the late Professor K. Becker, and some of the achievements are included in the recognized references [60, 61]. The current leader is Dr Henryk Anglart.

Applied Thermodynamics and Refrigeration

The research activities in this division concern a wide spectrum in energy and include system studies of city parts for development of components in refrigeration and heat pump systems. Applied topics concerning temperature and climate control in groceries as well as fundamental research on bubble formation in porous surface layers and two-phase flow in narrow ducts (microchannels) are carried out. Most of the work is related to heat pumping processes like refrigeration units and heat pumps. The current leaders are Professors Björn Palm (boiling/evaporation, microchannels, electronics cooling) and Per Lundqvist.

The late Professor Bo Pierre contributed in the 1950s and 1960s to establish the knowledge on heat transfer and pressure drop during boiling of refrigerants. From his experiments correlations were established, and these have frequently been cited in the relevant literature and used in engineering design. Unfortunately, most of the publications were in Swedish [62–64]. The original work concerned boiling of refrigerant R12 in horizontal copper tubes. His later experiments on boiling of refrigerants R22 and R502 confirmed the correlation. Experimental results from other researchers on R11 and methyl chloride also confirmed the correlation. Pierre gave correlations for the mean heat transfer coefficients as one correlation for complete evaporation and another one for partial evaporation. These read:

$$\mathrm{Nu_m} = 0.01 \times (\mathrm{Re}^2 \times \mathrm{K_f})^{0.4} \tag{4}$$

$$\mathrm{Nu_m} = 0.001 \times \mathrm{Re} \times \mathrm{K_f^{0.5}} \tag{5}$$

In Eqs. (4) and (5), $\mathrm{Nu_m} = \alpha_{\mathrm{mean}}\cdot d/\lambda$, $\mathrm{Re} = 4\cdot\dot{m}/(\pi\cdot d\cdot\mu)$, $\mathrm{K_f} = \Delta h/(L\cdot g)$ (referred to as Pierre boiling number), Δh is the change of enthalpy between inlet and outlet, L is he length of the tube, and g is gravity acceleration. The conditions for these equations were stated as: $\mathrm{Re}^2\cdot\mathrm{K_f} < 3.5\cdot 10^{11}$, $\mathrm{Nu_m} < 420$. More recently, the constants in Eqs. (4) and (5) have been changed as more accurate data for the thermophysical properties of the refrigerants became available.

Former Professor Eric Granryd (successor of Pierre, supervisor for Palm and Lundqvist) contributed on calculation procedure for finned tube heat exchangers. Unfortunately, his work was published in Swedish, but nevertheless it has received widespread notice. Granryd also initiated and led research projects on boiling and condensation for refrigerants and heat exchanger research with main applications in refrigeration and heat pump technology. Publications from this division are exemplified by references [62–76].

Nuclear Safety Division

Under the leadership of Professor Bai Raj Sehgal this division contributed significantly to research, including studies of severe accident phenomena in nuclear power plants; advanced multiphysics and multiscale simulation methods for coupled neutron-kinetic and thermal-hydraulic analysis of transients and accidents in nuclear reactors; experiments and analyses to support safety design of advanced nuclear energy systems; and basic research in boiling heat transfer. Several journal publications and Ph.D. theses have emerged from these activities. Some publications from this division are exemplified by references [77–79].

CONTRIBUTION FROM LINKÖPING INSTITUTE OF TECHNOLOGY—LINKÖPING UNIVERSITY, LINKÖPING

At the Division of Applied Thermodynamics and Fluid Mechanics some applied heat transfer problems with industrial relevance have been studied since the start of this university in the 1970s. These activities were started by senior lecturer D. Loyd (professor since 1995). Mostly heat conduction problems with specified convective or radiative thermal boundary conditions have been considered by the finite-element method. Examples of studies concern cool storage installation with phase-change material, industrial latent heat storage, thermal insulation to provide low temperatures for long time periods, slow-burning pyrotechnical compositions, and others. Nowadays the research includes analysis of flow and heat transfer processes with application in industry and medicine. Infrared (IR)–thermal detection of land mines and fuel-bed temperature determination in solid-fuel furnaces are considered, as well as influence of heat treatment on blood flow. The research encompasses modeling, simulation experiments in the laboratory, and and those at full scale. The current leader is Professor Matts Karlsson.

CONTRIBUTION FROM UMEÅ UNIVERSITY

At the Department of Applied Physics frosting phenomena in a model heat exchanger were investigated in the past. The study involved the influence on the frost growth of the air stream humidity, the air velocity, and the surface temperature. Also, the detoriation of the heat exchanger performance was studied and hydrophilic and hydrophobic coatings were considered. A conclusion was that the hydrophilic coating delayed the incipience of the frost formation.

ADDITIONAL CONTRIBUTIONS FROM LUND UNIVERSITY

Besides the work described under Frössling and Sundén, some other relevant work was carried out in the past.

At the former Division of Thermodynamics, Fluid Mechanics, and Heat Transfer, a Ph.D. project on cross-flow plate heat exchangers was carried out. In particular, the influence of the longitudinal wall heat conduction on the heat exchanger performance was investigated by mathematical/numerical and experimental methods; see reference [80]. This work has found practical application in a heat exchanger company. Another Ph.D. project was carried out on frosting in air gap flow passages; see reference [81].

Also, activities related to building heat transfer have been going on. Mainly heat conduction problems with specified convective heat transfer coefficients have been investigated numerically.

A more pioneering work has been carried out on heat transfer in food engineering applications. Professor B. Hallstrom was a leader for such activities.

CONTRIBUTIONS FROM INDUSTRIES

Many companies are spending significant amounts of resources on R&D on engineering heat transfer and fluid mechanics problems. In some companies big groups are handling such problems both computationally and experimentally. Among these companies are AB Volvo, Volvo Aero Corporation, Scania, ABB, Flakt AB, Ericson, Alfa Laval, SWEP, and others. However, most of these companies are involved in international competition and normally publishing is not permitted. Nevertheless, there have appeared some high-quality industrial works being published in the open literature that have received significant recognition. References [82–87] represent such.

FUNDING OF RESEARCH

Nowadays all faculty members at universities need to apply for funding in order to carry out significant research. The National Swedish Scientific Council (VR) and the Swedish Energy Agency are the major governmental funding organizations. Sometimes industry may give direct financial support for research, but in most cases it appears as in-kind financing, which might be quite useful in co-sponsoring projects receiving funds from the governmental agencies. Swedish researchers may also be partners or coordinators of frame projects being funded by the European Union (EU). The European Research Council (ERC) also is a possible financing body. However, heat transfer as a topic is not by itself an area of prime priority for funding agencies. Instead, it might be included in research programs of a much wider scope, like combustion processes and combustion engines; sustainable energy generation, supply, distribution, transportation; air-conditioning, and refrigeration; process industries; energy systems; efficient use of energy; and so on.

CONCLUSIONS

Past and current heat transfer research activities in Sweden have been summarized. Most activities are included in the Ph.D. educational programs at various universities. A variety of topics were dealt with. Some of the most significant contributions were highlighted. R&D work at industries is mostly confidential but still some significant contributions have appeared with good recognition.

NOMENCLATURE

CFD	computational fluid dynamics
d	tube inner diameter
Fr_1	Frössling number 1
Fr_2	Frössling number 2
g	gravity acceleration
Gr	Grashof number
IRT	infrared thermography
K_f	constant
L	tube length
LCT	liquid crystal thermography
LDV	laser Doppler velocimetry

$\dot{m}$	rate of mass flow
Nu	Nusselt number
PEMFC	polymer electrolyte membrane fuel cell
PIV	particle image velocimetry
Pr	Prandtl number
Re	Reynolds number
RTE	radiative transfer equation
Sc	Schmidt number
Sh	Sherwood number
SOFC	solid oxide fuel cell

Greek Symbols

α_{mean}	mean heat transfer coefficient
Δh	enthalpy difference
λ	thermal conductivity of fluid
μ	dynamic viscosity

Subscript

m mean

REFERENCES

[1] Frössling, N., Űber die Verdunstung fallender Tropfen, *Gerlands Beiträge zür Geophysik*, vol. 52, pp. 170–216, 1938.

[2] Ranz, W. and Marshall, W., Evaporation From Drops, *Chem. Engn. Progr.*, vol. 48, pp. 141–146, 1952.

[3] Frössling, N., Verdunstung, Wärmeübergang und Geswindigkeitsverteilung bei zweidimensionaler und rotationssymmetrischer laminarer Grenzschichtströmung, *Lunds Universitets Årsskrift, N.F.*, Avd. 2, vol. 36, no. 4, 1940.

[4] Frössling, N., Evaporation, Heat Transfer and Velocity Distribution in Two-Dimensional and Rotationally Symmetric Laminar Boundary Layer Flow, *Technical Memorandum, TM* no. 1432, NACA, 1958 (translation of NF2).

[5] Frössling, N., Calculation by Series Expansion of the Heat Transfer in Laminar Constant-Property Boundary Layers at Nonisothermal Surfaces, *Arkiv för Fysik*, vol. 14, no. 2, 1958 (Ph.D. thesis), Royal Swedish Academy of Sciences.

[6] Frössling, N., Calculation by Series Expansion of the Aerodynamic Heating at Laminar Constant-Property Boundary Layers, *Lunds Universitets Årsskrift, N.F.*, Avd. 2, vol. 54, no. 9, 1958.

[7] Frössling, N., Problems of Heat Transfer Across Laminar Boundary Layers, in *Theory and Fundamental Research in Heat Transfer*, ed. J. A. Clark, Macmillan, London, pp. 181–202, 1963.

[8] Frössling, N., Series Development and Finite Difference Calculations in the Laminar Boundary Layer, High Speed Computing in Fluid Dynamics, *Physics of Fluids Supplement II*, pp. II-133–II-136, 1969.

[9] Olsson, U., Laminar Flow Heat Transfer From Wedge-Shaped Bodies With Limited Heat Conductivity, *International Journal of Heat and Mass Transfer*, vol. 16, pp. 329–336, 1973.

[10] Modest, M., *Radiative Heat Transfer*, 2nd ed., Academic Press, New York, 2003.

[11] Leckner, B., Spectral and Total Emissivity of Water Vapor and Carbon Dioxide, *Combustion and Flame*, vol. 19, pp. 33–48, 1972.

[12] Sundén, B., A Theoretical Investigation of the Effect of Freestream Turbulence on Skin Friction and Heat Transfer for a Bluff Body, *International Journal of Heat and Mass Transfer*, vol. 22, no. 7, pp. 1125–1135, 1979.

[13] Sundén, B., Influence of Buoyancy Forces and Thermal Conductivity on Flow Field and Heat Transfer of Circular Cylinders at Small Reynolds Number, *International Journal of Heat and Mass Transfer*, vol. 26, no. 9, pp. 1329–1338, 1983.

[14] Sundén, B., The Effect of Prandtl Number on Conjugate Heat Transfer From Rectangular Fins, *International Communications in Heat and Mass Transfer*, vol. 12, no. 3, pp. 425–432, 1985.

[15] Sundén, B., and Karlsson, I., Enhancement of Heat Transfer in Rotary Heat Exchangers By Using Streamwise-Corrugated Flow Channels, *Experimental Thermal and Fluid Science*, vol. 4, no. 3, pp. 305–316, 1991.

[16] Olsson, C.-O., and Sundén, B., Heat transfer and pressure drop characteristics of ten radiator tubes, *International Journal of Heat and Mass Transfer*, vol. 39, no. 15, pp. 3211–3220, 1996.

[17] Gao, X., and Sundén, B., Heat Transfer and Pressure Drop Measurements in Rib-Roughened Rectangular Ducts, *Experimental Thermal and Fluid Science*, vol. 24, nos. 1–2, pp. 25–34, 2001.

[18] Wang, L., and Sundén, B., Performance Comparison of Some Tube Inserts, *International Communications in Heat and Mass Transfer*, vol. 29, no. 1, pp. 45–56, 2002.

[19] Utriainen, E., and Sundén, B., Evaluation of the Cross-Corrugated and Some Other Candidate Heat Transfer Surfaces for Microturbine Recuperators, *ASME Journal of Engineering for Gas Turbines and Power*, vol. 124, pp. 550–560, 2002.

[20] Jia, R., Saidi, A., and Sundén, B., Heat Transfer Enhancement in Square Ducts With V-Shaped Ribs, *ASME Journal of Turbomachinery*, vol. 125, pp. 788–791, 2003.

[21] Gao, X., and Sundén, B., PIV Measurements of the Flow Field in Rectangular Ducts With 60 Degree Parallel, Crossed and V-Shaped Ribs, *Experimental Thermal and Fluid Science*, vol. 28, pp. 639–653, 2004.

[22] Gao, X., and Sundén, B., Effects of Inclination Angle of Ribs on the Flow Behaviour in Rectangular Ducts, *ASME Journal of Fluids Engineering*, vol. 126, pp. 692–699, 2004.

[23] Jia, R., Sundén, B., and Faghri, M., Computational Analysis of Heat Transfer Enhancement in Square Ducts With V-Shaped Ribs—Turbine Blade Cooling, *ASME Journal of Heat Transfer*, vol. 127, pp. 425–433, 2005.
[24] Jia, R., Sundén, B., Leger, B., and Miron, P., A Numerical and Experimental Investigation of the Slot Film Cooling Jet With Various Angles, *ASME Journal of Turbomachinery*, vol. 127, pp. 635–645, 2005.
[25] Jia, R., Sundén, B., and Faghri, M., A New Low Reynolds Stress Transport Model for Heat Transfer and Fluid in Engineering Applications, *ASME Journal of Heat Transfer*, vol. 129, pp. 434–440, 2007.
[26] Haglund, C., Sundén, B., and Fahlen, P., An Experimental Study of Liquid Phase Heat Transfer in Multiport Minichannel Tubes, *Heat Transfer Engineering*, vol. 30, no. 12, pp. 941–951, 2009.
[27] Nilsson, K., and Sundén, B., Optimizing a Refinery Using the Pinch Technology and the Mind Method, *Journal of Heat Recovery Systems & CHP*, vol. 14, no. 2, pp. 211–220, 1994.
[28] Wang, L., Sundén, B., and Yang, T., Pressure Drop Analysis in Plate Heat Exchangers During Condensation, *Heat Transfer Engineering*, vol. 20, pp. 71–77, 1999.
[29] Wang, L., and Sundén, B., Design Methodology for Multistream Plate-Fin Heat Exchangers in Heat Exchanger Networks, *Heat Transfer Engineering*, vol. 22, no. 6, pp. 3–11, 2001.
[30] Rao, B. P., Sundén, B., and Das, S. K., An Experimental and Theoretical Investigation of the Effect of Flow Maldistribution on the Thermal Performance of Plate Heat Exchangers, *ASME Journal of Heat Transfer*, vol. 127, pp. 332–343, 2005.
[31] Sterner, D., and Sundén, B., Performance of Plate Heat Exchangers for Evaporation of Ammonia, *Heat Transfer Engineering*, vol. 27, no. 5, pp. 45–55, 2006.
[32] Sundén, B., Computational Fluid Dynamics in Research and Design of Heat Exchangers, *Heat Transfer Engineering*, vol. 28, no. 11, pp. 898–910, 2007.
[33] Xie, G., Wang, Q., and Sundén, B., Application of a Genetic Algorithm for Thermal Design of Fin-and-Tube Heat Exchangers, *Heat Transfer Engineering*, vol. 29, no. 7, pp. 597–607, 2008.
[34] Xie, G., Sundén, B., Wang, Q. W., and Tang, L., Performance Prediction of Laminar and Turbulent Heat Transfer and Fluid Flow Heat Exchangers Having Large Tube Diameter and Large Tube Row by Artificial Neural Networks, *International Journal of Heat and Mass Transfer*, vol. 52, nos. 11–12, pp. 2484–2497, 2009.
[35] Bobbili, P. R., and Sundén, B., Pressure Drop in Multi-Parallel Channels of Corrugated Plate Steam Condensers, *Heat Transfer Engineering*, vol. 30, pp. 1024–1032, 2009.
[36] Nilsson, T. K., and Sundén, B., Thermal Radiative Coefficients of Cylindrically and Spherically Shaped Soot Particles and Soot Agglomerates, *Heat and Mass Transfer*, vol. 41, pp. 12–22, 2004.
[37] Bahador, M., and Sundén, B., Investigation on the Effects of Fly Ash Particles on the Thermal Radiation in Biomass Fired Boilers, *International Journal of Heat and Mass Transfer*, vol. 51, pp. 2411–2417, 2008.
[38] Klason, T., Bai, X. S., Bahador, M., and Sundén, B., Investigation of Radiative Heat Transfer in Fixed Bed Biomass Furnaces, *Fuel*, vol. 87, nos. 10–11, pp. 2141–2153, 2008.
[39] Andersson, M., Yuan, J., and Sundén, B., Review on Modeling Development for Multiscale Chemical Reactions Coupled Transport Phenomena in Solid Oxide Fuel Cells, *Journal of Applied Energy*, vol. 87, pp. 1461–1476, 2010.
[40] Paradis, H., Andersson, M., Yuan, J., and Sundén, B., CFD Modeling Considering Different Kinetic Models for Internal Reforming Reactions in an Anode-Supported SOFC, *ASME Journal of Fuel Cell Science, Engineering and Technology*, vol. 8, June, paper no. 031014, 2011.
[41] Xie, G. N., Sundén, B., Wang, L., and Utriainen, E., Enhanced Internal Heat Transfer on the tip-wall in a Rectangular Two-Pass Channel (AR = 1:2) by Fin Arrays, *Numerical Heat Transfer, Part A*, vol. 55, pp. 739–761, 2009.
[42] Xie, G. N., Sundén, B., Utriainen, E., and Wang, L., Computational Analysis of Pin-Fin Arrays Effects on Internal Heat Transfer Enhancement of a Blade Tip-Wall, *ASME Journal of Heat Transfer*, vol. 132, no. 3, paper 031901, 2010.
[43] Xie, G., and Sundén, B., Numerical Predictions of Augmented Heat Transfer of an Internal Blade Tip-Wall by Hemispherical Dimples, *International Journal of Heat and Mass Transfer*, vol. 53, pp. 5639–5650, 2010
[44] Johansson, R., Andersson, K., Leckner, B., and Thunman, H., Models for Gaseous Radiative Heat Transfer Applied to Oxyfuel Conditions in Boilers, *International Journal of Heat and Mass Transfer*, vol. 53, pp. 220–230, 2010.
[45] Johansson, R., *Modeling Elements in Conversion of Solid Fuels—Fixed Bed Combustion and Gaseous Radiation*, Ph.D. thesis, Department of Energy Conversion, Chalmers, 2008.
[46] Andersson, K., *Characterization of Oxifuel Flames—Their Composition, Temperature and Radiation*, Ph.D. thesis, Department of Energy Conversion, Chalmers, 2007.
[47] Johnsson, F., *Fluid Dynamics and Heat Transfer in Fluidized Beds With Application to Boilers*, Ph.D. thesis, Department of Energy Conversion, Chalmers, 1991.
[48] Andersson, B. Å., *Heat Transfer in Stationary Fluidized Bed Boilers*, Ph.D. thesis, Department of Energy Conversion, Chalmers, 1988.
[49] Strömberg, L., *Calculation of Heat Flux Distribution in Furnaces*, Ph.D. thesis, Department of Energy Conversion, Chalmers, 1977.
[50] Berntsson, T., *Heat Transfer Studies in a New Type of Heat Exchanger for Divided Solids*, Ph.D. thesis, Department of Heat and Power Technology, Chalmers, 1976.

[51] Åsblad, A., and Berntsson, T., Surface Evaporation of Turbulent Falling Films, *International Journal of Heat and Mass Transfer*, vol. 34, no. 3, pp. 815–841, 1991.

[52] Melin, P., *Measurements and Modelling of Convective Vaporization for Refrigerants in a Horizontal Tube*, Ph.D. thesis, Department of Heat and Power Technology, Chalmers University of Technology, 1996.

[53] Johansson, M., *Heat Transfer and Hydrodynamics in Falling Film Evaporation of Black Liquor*, Ph.D. thesis, Department of Heat and Power Technology, Chalmers University of Technology, 2008.

[54] Johansson, M., Vamling, L., and Olausson, L., Falling Film Evaporation of Black Liquor under Evaporative Conditions, *International Journal of Heat and Mass Transfer*, vol. 52, pp. 2759–2768, 2009.

[55] Karlsson, T., and Vamling, L., Surprising Effects of Combined Vapour and Liquid Mass Transfer Resistances When Condensing a Mixture Outside Tube Banks, *International Journal of Heat and Mass Transfer*, vol. 48, pp. 403–412, 2005.

[56] Wellsandt, S., and Vamling, L., Prediction Method for Flow Boiling Heat Transfer in a Herringbone Microfin Tube, *International Journal of Refrigeration*, vol. 28, 6, pp. 912–920, 2005.

[57] Wellsandt, S., and Vamling, L., Heat Transfer and Pressure Drop in a Plate-Type Evaporator, *International Journal of Refrigeration*, vol. 26, 180–188, 2003.

[58] Gabrielli, C., and Vamling, L., Replacement of R22 in Tube-and-Shell Condensers: Experiments and Simulations, *International Journal of Refrigeration*, vol. 20, 3, pp. 165–178, 1997.

[59] Rosenblad, G., and Kullendorff, A., Estimating Heat Transfer Rates From Mass Transfer Studies, *Wärme und Stoffübertragung*, vol. 8, 3, pp. 187–191, 1975.

[60] Becker, K., Letzter, A., Nylund, O., and Schölin, B., An Experimental Study of the Effect of the Axial Heat Flux Distribution on the Dryout Conditions in 3650 mm Long Annulus, *International Journal of Multiphase Flow*, vol. 7, pp. 47–61, 1981.

[61] Becker, K., Enerholm, A., Sardh, L., Köhler, W., Kastner, W., and Krätzer, W., Heat Transfer in an Evaporator Tube With Circumferentially Non-Uniform Heating, *International Journal of Multiphase Flow*, vol. 14, no 5, pp. 575–586, 1988.

[62] Pierre, B., Värmeövergångstalet vid kokande Freon-12 i horisontella rör (Heat Transfer Coefficient for Boiling Freon-12 in Horizontal Tubes), *Kylteknisk Tidskrift, årgång* 12, December 1953 (in Swedish).

[63] Pierre, B., Strömningsmotstånd vid kokande köldmedier, *Kylteknisk Tidskrift*, no. 6, 1957 (in Swedish).

[64] Pierre, B., Värmeövergång vid kokande köldmedier i horisontella rör, *Kylteknisk Tidskrift, årgång* 28, no. 5, November 1969 (in Swedish).

[65] Palm, B., *Enhancement of Boiling Heat Transfer by Aid of Perforated Metal Foils*, Ph.D. thesis, Applied Thermodynamics and Refrigeration, KTH, 1991.

[66] Hambraeus, K., *Flow Boiling of Pure and Oil Contaminated Refrigerants*, Ph.D. thesis, Applied Thermodynamics and Refrigeration, KTH, 1993.

[67] Rohlin, P., *Zeotropic Refrigerant Mixtures in Systems and in Flow Boiling*, Ph.D. thesis, Applied Thermodynamics and Refrigeration, KTH, 1996.

[68] Shao, W., *Flow Condensation of Refrigerants and Refrigerant Mixtures*, Ph.D. thesis, Applied Thermodynamics and Refrigeration, KTH, 1996.

[69] Palm, B., Heat Transfer in Microchannels, *Microscale Thermophysical Engineering*, vol. 5, no. 3, pp. 155–175, 2001.

[70] Owhaib, W., Martin-Callizo, C., and Palm, B., Evaporative Heat Transfer in Vertical Microchannels, *Applied Thermal Engineering*, vol. 24, 8–9, pp. 1241–1253, 2004.

[71] Palm, B., and Claesson, J., Plate Heat Exchangers: Calculation Methods for Single- and Two-Phase Flow, *Heat Transfer Engineering*, vol. 27, 4, pp. 888–898, 2007.

[72] Martin-Callizo, C., Palm, B., and Owhaib, W., Subcooled Flow Boiling of R-134a in a Vertical Channel of Small Diameter, *International Journal of Multiphase Flow*, vol. 33, pp. 822–832, 2007.

[73] Ali, R., and Palm, B., Dryout Characteristics During Flow Boiling of R134a in Vertical Circular Minichannels, *International Journal of Heat and Mass Transfer*, vol. 54, pp. 2434–2445, 2011.

[74] Pierre, B., Flow Resistance With Boiling Refrigerants, Part I and II, *ASHRAE Journal*, pp. 58–65, pp. 73–77, September–October 1964.

[75] Granryd, E., Värmeövergång och tryckfall vid påtryckt strömning genom flänselement, *Kulde*, pp. 88–105, August 1965 (in Swedish).

[76] Granryd, E., Om val av seriekopplad rörlängd vid förångare med fullständig förångning, *Kylteknisk Tidskrift*, vol. 25, no 4, pp. 65–68, 1966 (in Swedish).

[77] Ma, W., Karbojian, A., Sehgal, B. R., and Dinh, T. N., Thermal-Hydraulic Performance of Heavy Liquid Metal in Straight-Tube and U-Tube Heat Exchangers, *Nuclear Engineering and Design*, vol. 239, 7, pp. 1323–1330, 2009.

[78] Sinha, R., Nayak, A. K., and Sehgal, B. R., Modeling of Natural Convection Heat Transfer and Dryout Heat Flux in Porous Debris Bed, *ASME Journal of Heat Transfer*, vol. 130, no. 10, 2008.

[79] Nayak, A., Sehgal, B. R., and Stepanyan, A., An Experimental Study on Quenching of a Radially Stratified Heated Porous Bed, *Nuclear Engineering and Design*, vol. 236, 19–21, pp. 2189–2198, 2006.

[80] Görtz, R., *Calculations and Measurements on Crossflow Heat Exchangers*, Ph.D. thesis, Division of Thermodynamics, Fluid Mechanics and Heat Transfer, Lund University, 1981.

[81] Andersson, I., *Theoretical and Experimental Studies of Frosting in an Air Gap*, Ph.D. thesis, Division of Thermodynamics, Fluid Mechanics and Heat Transfer, Lund University, 1992. (in Swedish)

[82] Marriott, J., Where and How to Use Plate Heat Exchangers, *Chemical Engineering*, vol. 78, no. 8, pp. 127–134, 1971.

[83] Marriott, J., Performance of an Alfaflex Plate Heat Exchanger, *Chemcal Engineering Progress*, vol. 73, 2, pp. 73–78, 1977.

[84] Holmberg, R., Heat Transfer in Liquid-Coupled Indirect Heat Exchanger Systems, *ASME Journal of Heat Transfer*, vol. 97, no. 4,pp. 499–503, 1975.

[85] Holmberg, R., Heat and Mass Transfer in Rotary Heat Exchangers With Nonhygroscopic Rotor Material, *ASME Journal of Heat Transfer*, vol. 99, pp. 196–202, 1977.

[86] Holmberg, R., Combined Heat and Mass Transfer in Regenerators With Hygroscopic Materials, *ASME Journal of Heat Transfer*, vol. 101, pp. 205–210, 1979.

[87] Holmberg, R., Sensible and Latent Heat Heat Transfer in Cross-Counterflow Gas-to-Gas Heat Exchangers, *ASME Journal of Heat Transfer*, vol. 111, pp. 173–177, 1989.

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