



**Proceedings of the 1961-62
HEAT TRANSFER CONFERENCE**

August 28 - September 1, 1961
UNIVERSITY OF COLORADO
BOULDER, COLORADO U.S.A.

January 8-12, 1962
CONTINUED DISCUSSIONS
CENTRAL HALL LECTURE THEATRE
WESTMINSTER,
LONDON, ENGLAND

*International
Developments in*
Heat Transfer

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
UNITED ENGINEERING CENTER
345 EAST 47th STREET NEW YORK 17, N. Y.

In each paper, numbers in brackets refer to the bibliography at the end of the paper; numbers in parentheses denote equations.

All equations, figures, tables and references of the discussors and rapporteurs can be readily identified in contradistinction to those of the original papers by a "D" preceding the number.

Appendices to papers 4, 7, 13, 33, 100, and 101 have been deposited with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington 25, D. C. Copies may be secured by citing the document number and remitting the amount stated on the first page of the articles. Advance payment is required. Make checks or money orders payable to: Chief, Photoduplication Service, Library of Congress.

Copyright © 1963 by
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
Printed in U.S.A.

Library of Congress Number 63-15594

International Developments in Heat Transfer

ARRANGED BY THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS,
AMERICAN INSTITUTE OF CHEMICAL ENGINEERS, THE INSTITUTION OF
MECHANICAL ENGINEERS AND THE INSTITUTION OF
CHEMICAL ENGINEERS

The International Heat Transfer Conference was held in Boulder, Colorado August 28-September 1, 1961, with a continuation of the discussion held January 8 to 12, 1962, Lecture Hall, Central Hall, Westminster, London, England. The purpose of this conference was to present new information in the field of heat transfer and the design of heat transfer equipment, particularly developments which have occurred during the previous decade since the General Discussion on Heat Transfer which was held in London in September, 1951.

The papers contained in this volume constitute those that were discussed in Boulder and later in London. The papers were summarized and/or alluded to by a reporter whose remarks set the tone for the discussion that followed. The discussion may have been written and submitted in advance, or was oral from the floor. The continuation of the discussion in London was for the convenience of those who would find it impossible to attend the main meeting in Boulder. To allow for the preparation of meaningful discussion, the papers were preprinted. All papers, together with the information stemming from the Boulder and London discussions, are now included in the Proceedings.

In addition to the formal papers, four special invited lectures were delivered in person at Boulder and London. The lectures and their subjects are as follows:

- Tuesday, August 29 - "Research During the Last Decade on Forced Convection Heat Transfer" by Prof. E.R.G. Eckert of the University of Minnesota.
- Wednesday, August 30 - "Some Reflections on Progress in Engineering Heat Transfer Science" by Prof. O.A. Saunders of the Imperial College, London.
- Thursday, August 31 - "Problems in Radiative Transport" by Prof. H.C. Hottel of the Massachusetts Institute of Technology.
- Friday, September 1 - "Heat Transfer by Natural Convection" by Prof. Ernst Schmidt of the Technische Hochschule in Munich.

The 124 papers and 4 lectures were presented in technical sessions arranged as follows:

- I. (A) Heat Conduction and Thermoelectric Effects
- II. (B) Heat Transfer in Equipment I
- III. (A) Boiling and Burnout, Condensation and Two-Phase Flow
- IV. (B) High Speed Flows, Aspects of External Convection, Vibrations and Pulsating Flows
- V. (A) Internal and Duct Flow
- VI. (A) Mass Transfer, Packed and Fluidized Beds
- VII. (B) Radiation, Thermal Properties and Instrumentation
- VIII. (A) Heat Transfer in Equipment II
- IX. (B) Free Convection

Responsibility for contacting authors and the review of manuscripts was divided geographically as follows:

American Organization Committee – North and South America, Japan and the U.S.S.R.

British Organization Committee – British Commonwealth (except Canada) and Europe

The Conference was sponsored by The American Society of Mechanical Engineers, American Institute of Chemical Engineers, The Institution of Mechanical Engineers, The Institution of Chemical Engineers with the participation of the American Chemical Society, The American Nuclear Society, American Rocket Society, American Society of Heating, Refrigerating and Air-Conditioning Engineers, The Chemical Institute of Canada, The Engineering Institute of Canada, Institute of the Aerospace Sciences, Society of Automotive Engineers, University of Colorado with the cooperation of the Rocky Mountain Sections, ASME and AIChE. Financial assistance of the National Science Foundation and the Office of Naval Research is acknowledged in making the meeting successful.

The Executive Committees appointed to organize the International Heat Transfer Conference are as follows:

The Joint Committee on North American Participation

Chairman: A. C. Mueller

Secretary: S. P. Kezios

American Chemical Society – J. W. Westwater

American Institute of Chemical Engineers – C. H. Brooks, S. W. Churchill,
T. B. Drew, O. E. Dwyer

The American Nuclear Society – W. H. Jens

American Rocket Society – T. F. Irvine, Jr.

American Society of Heating, Refrigerating and

Air-Conditioning Engineers – D. D'Eustachio

The American Society of Mechanical Engineers – G. M. Dusenberre*,

S. Koop, N. J. Palladino, T. L. Woolard

The Chemical Institute of Canada – W. H. Gauvin

The Engineering Institute of Canada – J. W. Stachiewicz

Institute of the Aerospace Sciences – P. Libby

Society of Automotive Engineers – P. T. Vickers

University of Colorado – B. H. Spurlock, Jr.

The British Organizing Committee

Chairman: O. A. Saunders

The Institution of Chemical Engineers – P. V. Danckwerts, A. J. V. Underwood

Institution of Electrical Engineers – A. R. Cooper, H. E. Upton

The Institution of Mechanical Engineers – J. F. Alcock, A. D. Baxter,

J. Diamond, A. J. Ede, A. W. Scott, D. B. Spalding, R. E. Zoller

*Deceased

Foreword

The safe and efficient transport of thermal energy is the objective of almost all industrial operations and indeed is crucial in the modern developments of atomic energy, high speed flight and space explorations. The papers presented at this conference represent the latest developments in heat transfer and were selected from many papers submitted from most of the major countries. These papers have been subjected to the critical evaluation of over 1200 registrants from 19 countries, and thereby become valuable as an authoritative collection. At the Boulder meeting there were 714 registrants representing 11 countries while at the London Continuation there were 520 registrants representing 18 countries.

The conference was opened in Boulder with welcoming remarks by W. H. Byrne, President of The American Society of Mechanical Engineers, and J. J. Healy, Jr., President of the American Institute of Chemical Engineers. O. A. Saunders, past President of the Institution of Mechanical Engineers and Chairman of the British Committee and P. W. Danckwerts, official representative of the President of the Institution of Chemical Engineers replied to the welcoming remarks. At the London Continuation the welcoming remarks were made by O. A. Saunders and P. W. Danckwerts and the response by W. H. Byrne and by A. S. Foust representing The American Institute of Chemical Engineers.

At the Wednesday Awards Luncheon in Boulder, Professor O. A. Saunders delivered The American Society of Mechanical Engineers Calvin Rice lecture and was awarded life membership with The American Society of Mechanical Engineers together with a certificate for the Calvin Rice Award. Certificates of appreciation were given to the other specially invited lecturers, Professors E. R. G. Eckert, H. C. Hottel and E. Schmidt. These lectures were delivered in Boulder following the luncheons while in London each presentation followed an afternoon tea. In addition, memorial remarks were made by the conference chairman for Max Jakob for his outstanding contributions in the field of heat transfer, for A. P. Colburn for his many studies and activities in the field of heat transfer, and for G. M. Dusenberre for his work and initial inspiration for this conference.

Numerous auxiliary functions formed parts of the conference. At Boulder the conference was welcomed by C. A. Hutchinson, acting Dean of Engineering of the University of Colorado and the history of Boulder was described by Forest Crossen of the *Boulder Daily Camera*. An informal banquet was held on Thursday evening with a discussion of world affairs by S. P. House, a former British Consul in Denver. Other social and family activities were sponsored since the Boulder location and conference time fitted in with vacation plans of many participants. In London a reception was held at the Institution of Mechanical Engineers on the opening day and special activities arranged for the visiting ladies. Overseas visitors were also invited to several receptions. A dinner for conference officials and authors was held on Thursday evening.

No formal presentation of papers was given at the conference, but a critical summary of the papers was given by two specially selected reporters (rapporteurs) for each session and the papers were then discussed from the floor. Preprinted papers were available at least six weeks before the conference to allow discussers to thoroughly prepare for the meeting, thus formal presentation of each paper was unnecessary and the major portion of each session could be devoted to discussion. These discussions together with the authors' replies form a part of these proceedings and were edited by special editors chosen for each session.

The general organization of the proceedings is as follows: First appear the four Special Lectures and these are followed by the body of Conference Papers, including Corrigenda, Reporters Remarks, and Discussions. The papers appearing are organized in their order of appearance on the program and they are numbered consecutively from 1 to 124 as a means of identification. These papers are grouped in Parts, five in all, each part representing the technical program for one day; they are identified by the Roman numerals I through V. Each Part consists

of Sections A and B representing the morning and afternoon technical sessions, respectively. Each Section (a technical session) represents material more or less related and it has associated with it a title representing the topical area(s) with which it dealt.

The main body of these proceedings is organized in the Parts I through V. Within each Part the papers for both Sections A and B appear first. The papers are immediately followed by the Corrigenda pertaining to them. The General Discussion then follows and it contains the Reporters Remarks, Discussion and Authors Replies in that order, all grouped into Sections A and B.

The pagination of all the Conference Papers is continuous from 1 to 1037 and the pagination of Corrigenda, Reporters Remarks, Discussions and Authors Replies is continuous from D-1 to D-314. In view of the organization of the proceedings, mentioned above, it is clear that the pagination of the papers is interrupted by the discussion material. In order to assist in locating items the discussion material is printed on tinted paper.

The following Editorial Committee was established to organize and edit the discussions, replies and other material and to check proofs of the materials going into these proceedings.

Part I — Section A — A. C. Mueller	Part IV — Section A — T. F. Irvine, Jr.
Section B — J. W. Westwater	Section B — T. B. Drew
Part II — Section A — N. J. Palladino	Part V — Section A — S. Kopp
Section B — W. H. Gauvin	Section B — S. P. Kezios
Part III — Section A — J. W. Stachiewicz	

The activities of this group were coordinated by the Secretary of the Committee on North American Participation.

Responsibility for the review of the papers appearing on the program fell to the American and British Committees. Each Committee was responsible for the review of manuscripts which arose from its geographical area of jurisdiction. In the case of the American Committee, two independent reviews were carried out, one by the Technical Society with which the paper was identified and another by the Committee itself. The Committee concerned itself only with papers accepted in the initial review. The persons responsible for the reviews by the Technical Societies are those listed as representatives of the cooperating societies. A Papers Subcommittee of the main Committee, made up of T. F. Irvine, O. E. Dwyer and P. Libby, served to coordinate the papers activities and make recommendations. The papers contributed through the British Organizing Committee were also reviewed in a thorough manner, the Committee assuming the role of referee. All final decisions on papers were the responsibility of the Committees.

The technical sessions were conducted by two Co-Chairmen for each session. A list of the Co-Chairmen is given below in view of the fact that their names do not appear elsewhere in these proceedings:

	BOULDER	LONDON
Part I (A) Session 1.	O. A. Saunders, A. C. Mueller	O. A. Saunders, A. C. Mueller*
(B) Session 2.	P. T. Vickers, J. W. Westwater	M. W. Thring, J. W. Westwater*
Part II (A) Session 3.	W. H. Jens, N. J. Palladino	E. S. Silver, N. J. Palladino*
(B) Session 4.	E. H. W. Schmidt, W. H. Gauvin	E. H. W. Schmidt, W. H. Gauvin*
Part III (A) Session 5.	J. W. Stachiewicz, B. H. Spurlock	G. Burnay, B. H. Spurlock
Part IV (A) Session 6.	T. F. Irvine, Jr., D. Q. Kern	M. B. Donald, T. F. Irvine, Jr.*
(B) Session 7.	T. B. Drew, B. Stewart	A. D. Baxter, T. B. Drew
Part V (A) Session 8.	J. A. Clark, S. Kopp	C. J. O. Garrard, S. Kopp
(B) Session 9.	P. V. Danckwerts, S. P. Kezios	A. J. V. Underwood, S. P. Kezios*

At the London Continuation, the discussion for each session already precipitated at Boulder and/or otherwise communicated prior to the meeting was reviewed and summarized by one of the Co-Chairmen from the Boulder meeting. These remarks followed the remarks of the Reporters and they served to bring the audience up to date on the nature and status of the discussion to avoid needless repetition. The Co-Chairmen who performed this function are design-

nated by an asterisk (*); their remarks do not appear in these proceedings. A. S. Foust summarized the discussion of Session 5, R. B. Stewart summarized Session 7 and J. A. Clark handled the summary for Session 8.

The Co-Reporters for each session are designated along with the texts of their remarks. Only the texts presented in connection with the Boulder meeting are printed here and they are identical with those given in London except for some minor variations which may have occurred in the following instances: Session 4 where O. A. Saunders remarked in place of L. Bernath; Session 5 where A. S. Foust remarked in place of A. L. London; and Session 6 where P. V. Danckwerts and D. Q. Kern remarked in place of C. Bonilla and A. S. Foust.

The organization of the American Committee stems from the joint ASME-AIChE Planning Committee for the National Heat Transfer Conferences held annually in the U. S. since 1957. For this international meeting a special committee was organized and representatives of participating societies added to the committee. The British Committee was organized by the Institution of Mechanical Engineers with participation of other engineering institutions. These two committees cooperated in the planning and execution of this conference. Primary staff responsibilities were carried by The American Society of Mechanical Engineers and the Institution of Mechanical Engineers. These meetings are made possible through the hard work of the committee personnel and due acknowledgment should be made to the companies and institutions of these men for permitting and encouraging this work.

Finally, it is desired to acknowledge the service of certain staff members of the Sponsoring Societies whose activities in the area of planning were noteworthy and whose assistance at almost every stage of the work was both necessary and valuable. The interest and strong support of Clarence Davies, Secretary of ASME until 1958, and Brian Robbins, Secretary of IMechE until 1960, was significant in the conception of the conference which was initiated in 1957. They provided the liaison between the working groups of the Sponsoring Societies and this activity ably carried on by O. B. Schier, II, successor of Mr. Davies, and K. Platt, successor to Mr. Robbins. Much valuable assistance and coordination was also received from T. A. Marshall, Jr., Senior Assistant Secretary of ASME until 1960, and R. Baldini, Assistant Manager of Meetings and Divisions, ASME. Also, R. Millson, Editor of Proceedings of IMechE, and J. Sansone, Head of Publications Control of ASME, assisted in a number of ways, especially with various aspects of the material for these proceedings.

In concluding, it was seen that the rapid strides in the field of heat transfer indicate that ten-year intervals between international meetings are too long. Plans have been formulated for having future international meetings in shorter intervals and that the meetings would alternate between Europe and the Americas.

A. C. Mueller, *Chairman*
S. P. Kezios, *Secretary*

February 20, 1963