Heat Transfer and Hydrodynamics in Gas-Cooled Fuel Rod Assemblies

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PREFACE

The twenty-seventh volume of the Thermophysics series is devoted to investigations of heat transfer, hydrodynamics, and flow mixing in gas-cooled fuel rod assemblies in longitudinal flow with a marked change in geometric characteristics of the cells along the assembly radius. The investigations were conducted at the Lithuanian Energy Institute for a number of years.

The book presents data of the experimental and theoretical study of local heat transfer and hydrodynamics in assemblies of smooth and rough rods, spaced using honeycomb spacer grids. Along with assemblies with spacer grids, consideration was given to assemblies with a wire wrapping.

Extensive experimental data made it possible to develop a number of universal calculating procedures and programs for the analytical cell-by-cell calculation of heat transfer and hydrodynamics in assemblies in longitudinal flow, the calculation of shear stresses at the wetted surfaces of assemblies, and the determination of local resistances of honeycomb spacer grids.

Special attention was given to the study of turbulent lateral mixing and structure of flow in rod assemblies with a wire wrapping.

The experimental setups and methods of study are described in detail. A part of the most characteristic experimental data is tabulated. The results are correlated in the form of calculational dimensionless similarity relations suitable for practical application. Recommendations are given for calculating the flow cross mixing in rod assemblies.

The integrated numerical and experimental study of thermohydraulic characteristics provided an explanation of some specific features of heat transfer and hydrodynamics in such complex systems. The obtained information is needed for improving the reliability of operation of various modern gas-cooled heat-transfer devices and will be useful in developing fuel assemblies of new nuclear reactors with various coolants.

The monograph incorporates results of the experimental investigations, conducted by the author together with Dr. J. Kolesnikov (Parts 5 and 6) and Dr. A. Sakalauskas (Parts 6 and 7).

I wish to express sincere gratitude to Academician Professor J. Vilemas for inestimable assistance in manuscript preparation; to reviewers Professor L.-B. Ašmantas and Professor A. Skrinska for thorough analysis of the present work and valuable remarks; to Dr. V. Smirnov and Dr. A. Bagdonas for direct participation in the development of methods and programs for the analytical calculations of the thermohydraulic characteristics of rod assemblies; and to all those who rendered assistance in preparing the monograph for print.

The monograph is devoted to the researchers and engineers working in the field of heat transfer, nuclear and chemical industry. The monograph will be useful to students, Ph.D. Candidates and university lectors as well.

Kaunas, 2005 B. Čėsna

CONTENTS

NOMENCLATURE

a – thermal diffusivity, m^2/s
A_c – area of the undisturbed flow, m^2
A_v – reduced area, m^2
d_1 – maximum dimension of the oval profile of the rod, m
d_h – hydraulic diameter, m
D_t – effective coefficient of diffusion
F – open area of the bundle, m^2
F_{rods} – total cross-sectional area of rods in the bundle, m^2
G, g – flow rate of the coolant, kg/s
acceleration due to gravity, m/s^2
i, h – enthalpy, J/kg
I – momentum transfer, $kg/(m^2 \cdot s)$
l – diffusion length, m
distinctive length, m
m – bundle porosity with respect to the coolant, F/F_{rods}
m_k – flow rate of the coolant in the k-th cell, kg/s
n – number of rods in the bundle
p_k – pressure in the cell, N
rem – root-mean-squere;
s – rod spacing, m;
T, t – temperature, K
pitch of the wire wrapping, m
u – flow velocity, m/s
x – bundle length, m
Q, q – heat flux, W/m^2
$y_{k,n}$ – width of the velocity profile, m
α – heat transfer coefficient, $W/(m^2 \cdot K)$
β_q – coefficient of interchannel mixing
β_v – coefficient of volumetric expansion

$\delta_{k,n}$ – characteristic momentum mixing length
Δh – pressure difference on the Pitot tube, N
ε_q, μ_q – thermal diffusivities, m/s
ε_τ, μ_τ – turbulent viscosities, m/s
ε – blockage ratio of the flow area, $\varepsilon = A_n/A_c$
φ – angle, °
χ – shape factor
λ – thermal conductivity of the coolant, W/(m·K)
ν – kinematics viscosity, m²/s
$\Pi_{k,n}$ – length of the gap in which the cells interact, m
ρ – density, kg/m
τ – shear stresses, N/m
ξ – resistance coefficient of the bundle
ψ – relative heat transfer coefficient
ζ – resistance coefficient of the spacer grid
Fr_m – dimensionless number, characterizing the intensity of the flow swirl in the bundle of rods with a wire wrapping (modified Froud number $\mathrm{Fr}_m = T^2/d_1 d_h$)
Pr – Prandtl number ($\mathrm{Pr} = \mu c_p/\lambda$)
Nu – Nusselt number ($\mathrm{Nu} = \alpha d_h/\lambda$)
Ra – Rayliegh number ($\mathrm{Ra} = g\beta_v \Delta t l^3/\nu a$)
Re – Reynolds number ($\mathrm{Re} = u d_h/\upsilon$)
Le – Lewis number ($\mathrm{Le} = \rho c_p D_t/\lambda$)
St – Stanton number ($\mathrm{St} = \alpha/c_p \rho u$)

Subscripts and superscripts

∞ – in the free flow
ad – adiabatic
b – bundle
c – calculated
ch – channel
cr – critical
en – entrance
ex – experiment
f – conditions as to the flow temperature
i – cell number
is – isolation conditions

j – surface number
k,n – between the cells k and n
lar – laminar
q – heat
r – rough
ran – random
rem – root-mean-squere
ss – self-similar
sg – spacer grid
sh – shell
sm – smooth
st – stabilization
$syst$ – systematic
t – tube
ts – two-sided
w – conditions at the wall
τ – friction

Abbreviations

DARS – Lithuanian abbreviation for calculation of gas-cooled reactors
FA – fuel assembly
MVL – maximum velocity line
N – normal
PMV – point of maximum velocity
PN – principal normal
SG – spacer grid

1

Introduction

The arrangement of fuel elements in the form of rod assemblies found wide application in reactor engineering. Such assemblies are used in the most diverse reactors, such as water-moderated, boiling water, gas-cooled, and liquid-metal cooled reactors of both vessel and channel structure. The international group, representing the governments of ten nuclear countries, chose six concepts of the joint development of the next (IV) generation of power reactors [1]. According to the conclusions reached at the International Forum, all concepts of the IV generation of reactors can be implemented by 2030, and some of them even by 2020. Basic diagrams of two types of reactors of the new generation are presented in Figs. 1.1 and 1.2.

The first is a helium-cooled reactor operating in the fast-neutron spectrum and having a closed fuel cycle (Fig. 1.1). The helium temperature at the core exit reaches 850°C. The recommended electric power of the reactor is 288 MW(e). The reactor operates in combination with a steam turbine with the Brayton cycle, which has a high efficiency.

The second is a supercritical water-cooled reactor (Fig. 1.2), which is operated at supercritical parameters of water (374°C and 22.1 MPa). The supercritical water coolant makes it possible to increase the thermal efficiency of this reactor by one third in comparison with the present-day light-water reactor. This implies that the energy balance of the electric power plant significantly simplifies, since the phase state of the coolant in the reactor does not change. The recommended electric power of the reactor is 1700 MW(e). The reactor is operated at a pressure of 25 MPa, and the coolant temperature at the core exit reaches 510-550°C.

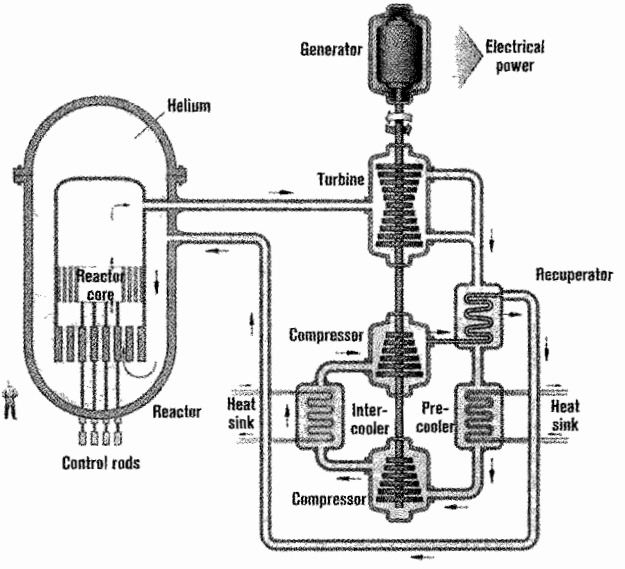

FIGURE 1.1. Gas-cooled fast reactor

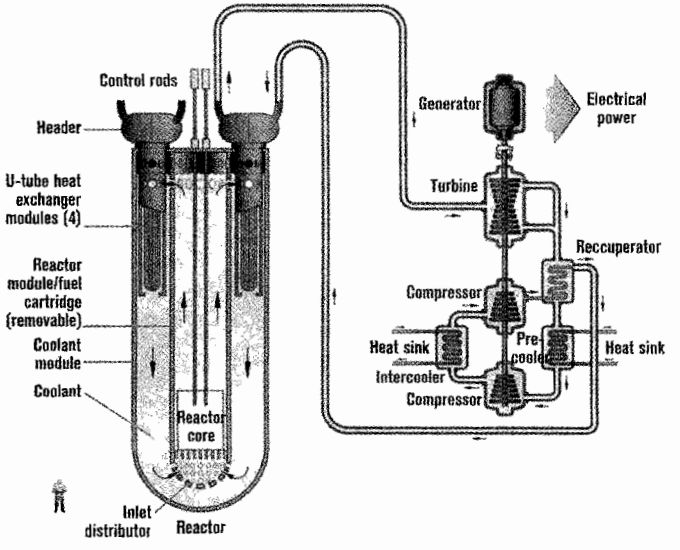

FIGURE 1.2. Supercritical water-cooled reactor (SCWR)

Of great importance for assessing the prospect of the development of nuclear power engineering are investigations of heat transfer and hydrodynamics in various gas-cooled assemblies at large heat loads. Because of the complicated geometry of rod assemblies, the laws governing heat transfer and hydrodynamics in them are markedly different from those for channels of simple shape (like annuli and tubes of various cross sections), and until now have not received sufficient study.

The specific features of heat transfer in rod assemblies in the longitudinal flow of a gaseous coolant or vapor are relatively low heat transfer coefficients, significant heatings of the coolant along the assembly length, and relatively weak heat and mass transfer in the bundle cross section, which, in turn, leads to large temperature differences in the cross section and to a substantial temperature nonuniformity of the fuel-element shell. In gas-cooling assemblies, the geometrical parameters, operating conditions, and structure of the assembly itself have a stronger effect on the temperature field. Dissimilar geometry of the interconnected cells, the presence of a smooth unheated shell, a different heat release in the fuel elements, the proximity of a smooth shell and rough rods in the assemblies with heat transfer intensifiers, and a variety of other factors cause appreciable nonuniformities in the distribution of mass velocities and heat and vapor contents of the coolant over the cross section of the channels, which is the reason for a large temperature nonuniformity in various elements of the assembly and can cause a significant deformation of the rods. Flow is markedly influenced by such structural elements of the assemblies as spacer grids, wrapping, finning, etc. All of these features manifest themselves most clearly in few-rod assemblies. They can lead to the considerable decrease of efficiency and reliability of the reactor. Therefore, among the main tasks in producing cores in the form of rod assemblies cooled by gas or vapor, is to equalize the temperature field in the cross section of the assembly and accurately determine its local values.

The provision of high efficiency and reliability of operation of the gas- or vapor-cooled fuel assemblies is an important problem whose solution depends to a certain extent on the level of the technical justification. This is especially relevant to assemblies operating in high-temperature modes. The uncertainty of some parameters requires a deeper insight into the thermophysical processes, beginning with assemblies in longitudinal flow and the study of new phenomena that conforms to the contemporary scientific level. The interchannel hydrodynamic and heat

exchange, a variable energy release, deformed rod lattices and nonstandard elementary channels, the roughness of rods or the application of fins to them, regular and stochastic temperature nonuniformities, the related superheating factors and hot spots – this is by far not a complete list of the questions currently posed by the practice of nuclear power engineering in designing gas-cooled assemblies in longitudinal flow.

Accounting for the enumerated factors in the thermohydraulic calculation of assemblies is a very complex problem. The following requirements are imposed on the thermohydraulic calculations:

- great informativeness,
- high reliability of results, primarily for local hydrodynamic and thermal characteristics, since, on the one hand, large margins of the wall temperature are inadmissible (the power and efficiency of the plants are limited) and, on the other hand, the excess of local temperatures above permissible limits can result in the superheating of the assembly or its individual elements and in the failure of the entire assembly.

The prerequisite for securing the operational safety of the assemblies under extreme conditions is the fulfillment of limitations on the maximum temperature level of the rod surface. Correspondingly, high requirements are also specified for the thermophysical justification of assemblies. The fulfillment of limitations, not only on average parameters but also on their deviations from nominal values, necessitates the study of the effect of the deviations on the temperature fields of assemblies.

The temperature deviations from nominal values because of the superheating of fuel elements can be determined using two methods. The first of them is analytical. This method is applied to calculating the deviation of the known temperature function depending on many random parameters (factors) by specified laws and distributions. The second is the statistical Monte Carlo method.

The analytical method is faster than the Monte Carlo method. However, it noticeably limits the functional dependence of temperature on various parameters. The Monte Carlo method is expedient to use where the dependence of temperature on the governing parameters is multidimensional and nonlinear, and random deviations of the parameters are significant and obey the law of free distribution under all general conditions.

It is also expedient to use the superposition method, with which temperature deviations as a result of the effect of local factors are deter-

mined by the Monte Carlo method and total temperature deviations are evaluated analytically.

Among the steps of the justification of assemblies in longitudinal flow is the analytical determination of thermohydraulic characteristics of assemblies and their elements. The analytical description incorporates the calculations of geometric characteristics of assemblies and the distribution of the coolant flow rates and heatings among elementary channels of the assembly with accounting for the interchannel hydrodynamic and heat exchange, the determination of the wall-gas temperature differences, and finally, consideration of the effects of various factors on the temperature field. Since the coolant heatings in gas-cooling assemblies are very large (over 200°C), the accuracy of determining the maximum temperature of the rod surface depends to a considerable extent on the correctness of the calculation of the distribution of the coolant heating in elementary cells.

The processes of the formation of the velocity and temperature fields in assemblies in longitudinal flow that represent a system of interconnected channels, exchanging mass, momentum, and heat, have essential distinctions from the processes in isolated channels. Random geometrical deviations (for example, deflections or displacements of the rods) result in a local redistribution of the coolant flow rates among elementary cells. The rod spacing elements (such as spacer grids and a wire wrapping) affect the interchannel mixing and the degree of flow turbulence. Nonuniformity of the coolant distribution among various-geometry cells (like central and peripheral cells) is determined by the hydrodynamic characteristics of the interconnected channels.

The role of various factors causing the flow nonuniformities changes with the type of the device and structure of the fuel assemblies. A high thermal stress of such assemblies and the presence of spacing facilities in them lead to instability of hydrodynamics and heat transfer along the channel length. However, these factors cannot be taken into account based on a one-dimensional representation of the hydraulics of the fuel assembly, since a more complete and comprehensive description of the coolant flow is needed.

The use of the procedures and equations for isolated channels in calculating interconnected channels can lead to large errors. Therefore, it is necessary to develop special procedures, taking into account the features of such interconnected channels.

Interchannel heat and mass transfer are important factors behind the formation of the thermal and flow pictures of assemblies in longitudinal flow. For example, spiral wire wrappings on rods, which make contact with the surfaces of neighboring rods, decrease the temperature in the region of hot spots and thus facilitate an increase in the assembly power. None of the present-day procedures of the thermophysical calculation of assemblies can do without accounting for this factor. Its importance manifests itself when consideration is given to the processes occurring both inside the rod assembly and in the space between individual rod assemblies (for example, the interaction between fuel assemblies in a nuclear reactor).

The cellular method is equivalent to the difference method of solving differential equations. However, there is a basic distinction between them. In the difference method, there is an opportunity for reducing the grid step, and thus the solution obtained using the difference method can be brought as close to the solution of the starting differential equation as desired. In the cellular method, the minimum step size of the grid is limited by the cell dimensions.

Regardless of the above-mentioned drawbacks, the cellular methods are now an effective instrument in the calculation of local thermohydraulic characteristics of rod assemblies. Within the framework of these methods, the question remains open as to the determination of dependences for calculating local thermohydraulic parameters of cells, especially for assemblies with hydraulically nonequivalent cells, i.e., dependences for

- the distribution of the local skin friction coefficient,
- the local heat transfer coefficient,
- the turbulent coefficient of mixing between cells,
- the coefficient of hydraulic resistance of spacer grids and their effect on the above dependences.

In order to further refine such methods, it is necessary to solve the problem of thermohydraulics for a number of cross sections of the assembly, retaining average values of the thermohydraulic parameters in the cells. The development of more accurate calculational methods requires the experimental study of local hydrodynamic characteristics in rod assemblies with thermohydraulically nonequivalent cells. Most of the known experimental studies of this problem pertain to fuel assemblies with equivalent cells.

1.1. Analysis of Methods of the Thermohydraulic Calculation of Rod Assemblies

Methods of the three-dimensional analysis of hydrodynamics and heat transfer in rod assemblies

A detailed thermohydraulic calculation of fuel rod assemblies is needed not only for conducting the developments but also for processing the results of experiments, which model these fuel assemblies or their fragments. To date, a great many calculating procedures have been worked out that make it possible to determine, to various degrees of adequacy, the coolant parameters and the wall temperatures at any point in the fuel assembly. Three principal trends can be distinguished in the development of the methods of solving such problems: the first is a detailed theoretical and experimental description of the hydrodynamics of the interrod space, the second is the method of homogenization or of porous body that is used mainly for multirod assemblies of complicated geometry [2], and the third is the method based on the splitting of the cross section of the channel of a complicated shape into elementary channels (cells) that make contact with one another in the narrowest cross section.

A detailed description of the first trend is given in monographs [3, 4]. It should be noted that in connection with the complication of the geometries of elements of the reactor cores and nonuniformity of local thermohydraulic characteristics of flow, only a limited range of the problems of hydrodynamics and heat transfer can be solved at present. The second method – the method of homogenization [5-7] or of porous body – can be used for calculating the spatial temperature field in the fuel assembly, averaged on the elementary cell scale. The essence of this method is that flow in the rod bundle is viewed as being two-phase with an immovable solid phase and volumetric sources of energy release, and with accounting for friction. In this model, friction is taken into account and local conditions of the rod cooling are disregarded.

According to the third method, the rod bundle on the whole is considered as a system of parallel communicating channels. In the English literature, the term "subchannel" is used to denote the forming channels; it is not employed in the Russian literature. In the Russian literature it is customary to use the term "channel" or "cell," adding "elementary," if needed, in order to stress that a mentally isolated part of the actual channel is spoken of. Mass momentum and energy balance equations

are written for each such channel. Variations in the flow parameters (such as mass velocity and temperature) within the limits of a single cell are neglected. Using this procedure, many diverse computer programs of such purpose have been developed in various countries that are based on approximately identical thermohydraulic models of flow. This method and the programs are considered in greater detail in reviews [8-11]. A significant part of the presented algorithms is intended for analysis of evaporation channels, and as a rule, the programs suggest an arbitrary number of elementary cells. Although many programs have been developed independently, they have much in common. Common are the methods of dividing the cross section into elementary cells (at present, it is customary to draw the cell boundaries in the gaps between rods along the lines, connecting the rod centers). For peripheral cells, it is customary to draw the boundary along the lines, passing through the rod center to the angular point, or normal to the shell. However, there are programs, for example, the Italian CISE [12], in which cells are isolated along the maximum velocity lines. In this case, the fuel rod is fully inside the cell (Fig. 1.3).

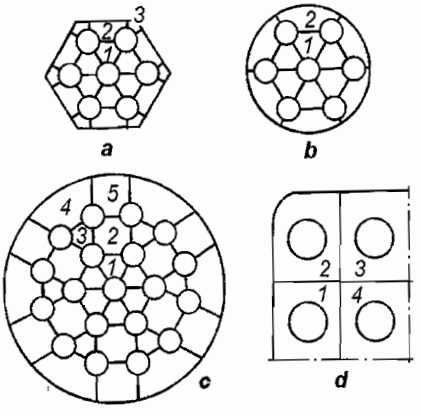

FIGURE 1.3. Examples of the division of the cross sections of various channels into elementary cells. (*a*), (*b*), and (*c*), division along the lines, connecting the rod centers; (*d*), division along the zero-stress lines

Since the mass, momentum and energy balance equations can be written for any part of the channel, the method of isolating elementary cells is not important. However, for closing these equations it is necessary

to use empirical dependences of the flow interaction that are studied under quite certain geometric conditions.

The stresses at the solid surfaces, confining the cell, are determined using ordinary hydraulic dependences. The determining dimension is taken to be the hydraulic diameter calculated from the wetted perimeter of the cell. Some authors [3, 4] suggest that corrections be introduced that allow for the difference of the cell shape from a circular channel. These corrections are determined using the results of hydrodynamic studies.

In the considered approach, the thermal and mechanical interaction of flows at the cell boundaries are taken into account. In describing this interaction it is necessary to determine the rate of the interchannel transfer. However, both theoretical and experimental determinations of the rate of the interchannel transfer involve great difficulties primarily because of the complexity of its mechanism. Mass and heat transfer between channels results not only from turbulent or diffusive exchange, but also from the effect of the directional cross flow caused by the pressure gradient in the region of transient flow (inlet sections, regions near spacing elements) or by the deviation of geometric dimensions from nominal values (the deformation of channels, the swelling of rods, etc.).

In the last year, a novel method of calculating thermohydraulic parameters of assemblies has been developed, namely, the method of large vortices, reviewed in Ref. [13]. This is a method of direct numerical modeling used for studying the mechanisms of some flows and obtaining data on the turbulent statistics with reference to the development of statistical turbulence models. The method of large vortices is used for modeling flows at high Re and Ra numbers. The drawback of this method is a strong dependence of the subgrid scale for low Re numbers on the accuracy of the employed models.

The most commonly used programs for the thermohydraulic analysis of rod assemblies by the channel-by-channel method

The need for solving the above problems prompted the appearance of a variety of programs, developed for a computer. The development was conducted independently in various countries and firms. Basic principles remained common, but specific implementations of the physical models and calculational methods turned out to be very diverse. This made it possible to accumulate by now great experience on the evaluation of specific features and ranges of application of various methods.

Information on the most widely known programs is presented in Table 1.1.

Table 1.1
Programs for thermohydraulic calculation of rod assemblies using channel-by-channel method

Program	Author, reference	Year	Country	Note
HAMBO	R.W. Bowring [14]	1967/68	England	
TIGR	N.L. Polyanin [15]	1969	Russia	For uniphase coolants
CISE	G.R. Gaspari et al. [12]	1970	Italy	
GIDRA	V.S. Osmachkin et al. [16]	1970	Russia	
COBRA - IIA	C.L. Wheeler et al. [17]	1970	USA	For multirod assemblies
FORMAX	A.W. Graves et al. [18]	1972	USA	For assemblies with wrapping
EBRFLOW	A. Gopalakrishnan et al. [19]	1973	USA	For a 37-rod assembly
FORCMX	A.W. Graves et al. [20]	1973	USA	For assemblies with wrapping
PUCHOK-2	Yu.V. Mironov et al. [21]	1973	Russia	For uniphase assemblies
HERA	R. Nijsing et al. [22]	1974		
DIANA	S. Hirao et al. [23]	1974	Japan	For multirod assemblies
PUCHOK-3	Yu.V. Mironov et al. [24]	1979	Russia	For multirod assemblies
NADJA	G. Cornet et al. [25]	1976	Belgium	
PUCHOK BM	G.S. Mingaleyeva et al. [26]	1980	Russia	For multirod assemblies
PUCHOK BM-RIP	G.S. Mingaleyeva et al. [27]	1981	Russia	For multirod assemblies
BREED	A.S. Chichkanov [28]	1980	Russia	
SIMPL - 2	O. C. Jones et al. [29]	1977	USA	
SAGAPO	M.Dalle Donne et al. [30]	1977	FRG	
SCRIMP	M. Huggenberger [31]	1977	Switzerland	
SAGAPO - 2	A. Martelli [32]	1978	FRG	
CLUHET	P. Barroyer [33]	1981	Switzerland	
	R.V. Snitsar [34]	1995	Russia	For laminar flow
DARS	B. Česna [35]	1999	Lithuania	For multirod assemblies and uniphase coolants

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