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GCFR THERMAL-HYDRAULIC EXPERIMENTS

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MASTER

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ABSTRACT

This paper reviews the thermal-hydraulic experimental studies performed and planned for the Gas-Cooled Fast Reactor (GCFR) core assemblies. The experiments consist of basic studies performed to obtain correlations, and bundle experiments which provide input for code validation and design verification. These studies have been performed and are planned at European laboratories, U.S. national laboratories, Universities in the U.S., and at General Atomic Company.

This review shows that the experimental program planned for the GCFR core thermal-hydraulic will provide sufficient information for design analysis and verification of GCFR core assemblies.

1.0 INTRODUCTION

The Gas-Cooled Fast Reactor (GCFR) core assemblies consists of metal-cladded fuel and blanket rods. Pressurized helium flows over these assemblies in axial direction. To improve the heat transfer characteristics of the gaseous coolant, the fuel rod outer surface is roughened over the active core length. In the radial blanket, because of lower heat fluxes, roughening is not utilized, but wire-wrap spacers are used to obtain close rod spacing required to achieve high heavy metal volume fractions. Hence, the GCFR thermal-hydraulic core performance predictions require the understanding of thermal and fluid flow characteristics associated

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All the individual programs mentioned are being coordinated into a joint international thermal-hydraulic development in support of the US GCFR. An important ingredient of this joint international program is the organization of benchmark calculations. The purpose of the benchmark rounds are to ensure proper transfer of the expertise gained from the experiments and to develop correct analytical performance prediction models and code applications for GCFR core assemblies.

Additional experiments focusing on bundle behavior under accident conditions are planned at Los Alamos Scientific Laboratory (LASL). These are the Steel Melting and Reduction Tests (SMART, Ref. 10), Depressurization Accident Condition Tests (DACT, Ref. 11), and Natural Circulation Tests (Ref. 12).

The programs mentioned above are described in brief in this paper.

2.0 BASIC TESTING

2.1 SINGLE ROD EXPERIMENTS

The most convenient configuration to obtain basic heat transfer and pressure drop correlations for rough surfaces is an annulus composed of a single roughened rod and a smooth outer tube (Fig. 1). A transformation method has to be applied to separate the rough surface effects.

A large number of different artifically roughened surfaces were tested in air in annular channel geometries (Refs. 13, 25). The tests included a wide variation of rib height, pitch, and width. Also, the effects of roughness fabrication techniques were tested (Ref. 14). A performance index of rough surfaces was developed (Ref. 14) and was used to define an optimum roughness configuration for the GCFR. This configuration is characterized by a trapezoidal shape of the individual rib and the following geometry ratios, where the rib height depends on rod diameter and lattice spacing:

Rib width-to-height ratio = 3.5
Rib pitch-to-height ratio = 12.0

An example of the GCFR roughness shape using the above ratio is shown in Fig. 2.

The roughness shown in Fig. 2 is referred to as a 2-dimensional roughness. Recently a 3-dimensional roughness has been proposed (Ref. 32) which has a potential for improved performance. Single-rod tests with this roughness have been completed.

After completion of the independent single-rod tests, the performance measurements of roughened rods were continued with a typical GCFR roughness in a joint KfK-EIR experiment. The prupose of this experiment was to improve the accuracy of experimental results by exploring the effects of (1) different gases, (2) measurement techniques, and (3) high Reynolds numbers. The results are summarized in Figs. 3 and 4, which show that in the typical GCFR Reynolds number range (5×10^4 to 10^5) the scatter band is on the order of ± 7% for friction and ± 3.5% for heat transfer (Ref. 28). Single-rod experiments will be performed testing a prototype of the roughened cladding designed and built for the CFTL Program. The purpose of the experiment is to determine the coefficients for the friction factor and heat transfer correlations for the particular roughness geometry used in the CFTL. These coefficients will be determined using a method suggested in a recent study (Ref. 33).

2.2 SPACER TESTS

Spacers are used to position the individual rods within a bundle. There are basically two kinds of spacer systems: grid spacers and the wire-wrap system. Their application depends on the spacing available between the rods. The GCFR conceptual design uses grid spacers for the fuel assemblies and the wire-wrap system in the radial blanket assemblies.

2.2.1 PRESSURE DROP EFFECTS ON GRID SPACERS

Several types of grid spacers have been tested as shown in Table 2 (Refs. 15-19, 27-29). The tests were conducted with different fluids and different size bundles. The spacers tested differed in web band geometry. While the regular hex spacer has straight web bands and large buttons for rod support, the modified hex spacer employees bent web bands such that the buttons can be small. Hex-shaped spacers provide support cells for each individual rod, where as rhombic spacers combine four rods into each cell with alternative rod combination at adjacent spacer levels. The pressure drop measured was found to depend on:

(a) type of spacer

(b) relative spacer blockage in each individual subchannel

(c) rod surface condition, i.e., either smooth or rough

(d) flow Reynolds number

An analytical model was developed (Ref. 20) to predict the spacer loss coefficient. This model is comprehensive and has been verified with all experiments shown in Table 2. Using this model, the pressure drop of the GCFR type spacer grid were analyzed and the results were compared with experimental data (F[illegible] 5). The comparison indicates a close agreement.

2.2.2 HEAT TRANSFER EFFECTS OF GRID SPACERS

The influence of a particular spacer geometry on the local heat transfer from smooth and rough rod surfaces was first investigated in an annular test section (Ref. 21). The main result from those tests was the finding that there are "cold spots" rather than hot spots under each spacer for both smooth and roughened rods. The studies were extended to cover a wide range of Reynolds numbers and flow blockage ratios; a 3-rod bundle arrangement was tested in air; correlations were derived to include the heat transfer improvement near and under spacers in the analytical models (Ref. 3). An example of these data is shown in Fig. 6.

2.2.3 EFFECT OF WIRE-WRAP SPACERS

The major portion of data for pressure and temperature distributions in wire-wrapped rod bundles is available from the US Liquid Metal Fast Breeder Reactor (LMFBR) program. To expand the data range to include GCFR type pitch-to-diameter ratios and Reynolds numbers, water tests were conducted using a full size GCFR blanket assembly (Ref. 5). In these experiments, emphasis was placed on pressure drop, heat transfer, and coolant mixing. The main conclusions are: (1) the pressure drop in the turbulent flow regime is consistent with LMFBR data and at low Reynolds numbers laminar flow correlations for smooth tubes can be used; (2) For the description of heat transfer in the turbulent flow regime a new correlation was developed, and at low Reynolds numbers, laminar correlations for smooth tubes can be used, also circumferential variations of heat transfer were used to refine the hot spot temperature predictions; (3) The wire wrap flow mixing tested with GCFR blanket geometry appeared to be significantly less than that reported for the LMFBR; this effect can be attributed to a longer wire pitch in the GCFR; and (4) The axial pressure profile measurements were used to modify the COBRA-IV code to obtain better agreement between code prediction and experimental data.

2.3 MIXING TESTS

Mixing tests have been conducted to investigate mixing caused by turbulence and cross flows in rod bundles (Ref. 22). These tests together with results reported in the literature provide data to model flow mixing effects in the subchannel codes used for thermal-hydraulic analysis of the GCFR assemblies. Further review of this subject in progress by the benchmark group (Section 3.2).

2.4 OTHER STUDIES

In addition to the above studies which lead to specific correlations, experiments were conducted to study the effect of rib shape on flow distribution around the rib (Ref. 7). The studies consisted of flow visualization in air with various rib shapes under consideration for GCFR use. The studies resulted in some recommendations regarding the optimum rib shape, which are consistent with earlier findings.

Analytical calculations of pressure drop in the inlet nozzle of the core assemblies are difficult due to the complicated shape. Isothermal experiments with air have been conducted to explore the flow characteristics and to confirm the calculations (Ref. 8).

2.5 DATA TRANSFORMATION

The pressure drop and friction factor data obtained from single rod experiments described in Section 2.3 have to be transformed to separate the effects of rough and smooth surfaces. The usual procedure divides the flow into two zones separated by a line of zero shear. Figure 1 illustrates such a division of the annulus into two zones. If the location of zero shear is known, various quantities required to separate the effects of smooth and rough surfaces can be calculated. A number of methods to achieve this have been proposed in the past two decades; they are summarized in Ref. 34.

One of these methods (Ref. 25) has been adopted by GA. Recently, a modification to this procedure has been proposed (Refs. 33, 34) which will be verified during further experiments.

3.0 CODE DEVELOPMENT

For the design of the GCFR core assemblies, it is necessary to accurately predict the pressure and temperature distribution within these assemblies under a wide range of operating conditions. Because of the complicated geometry and a variety of effects (i.e., spacer effects, turbulent mixing, rod conduction, radiation heat transfer, etc.), an exact solution of the differential equations governing the fluid behavior in the assemblies is not possible.

It is necessary to develop computer codes which take the individual effects into consideration, subdivide the bundle into subchannels, and solve the governing differential equations by numerical methods. Current codes for use in the GCFR program are:

CODE	DEVELOPER	REFERENCE
COBRA*GCFR	GA	35
CLUHET	EIR	36
SCRIMP	EIR	37
SAGAPO	KfK	38

During the past four years, considerable improvement in these codes has been achieved utilizing experimental results from small-bundle tests. This program consists of bundle experiments and benchmark calculations. Major parts of this program are described below.

3.1 BUNDLE EXPERIMENTS

As discussed in Section 2, the basic experiments lead to thermal-hydraulic correlations which are used in the subchannel codes for assembly analysis. The verification of the codes can only come from comparison of code analyses with bundle experiments. To achieve this, a number of bundle experiments have been undertaken and further tests are planned with GCFR type assemblies.

The tests conditions and current status of these tests are summarized in Table 3. In addition to the bundle tests summarized in Table 3, accident analysis tests planned are described in Section 3.4. Detailed description of all tests is not possible here. However, due to importance of CFTL tests (Ref. 9) to the GCFR program, these are described below in brief.

Within the thermohydraulic development program, the CFTL (Ref. 9) has the following objectives:

(a) Test models of the GCFR fuel, control and blanket assemblies under normal, upset, emergency, and faulted design conditions

(b) Validate the analytical methods employed to predict the performance and cyclic behavior of the full size GCFR core assemblies under normal, upset, emergency, and faulted design conditions.

(c) Determine unknown core assembly performance deficiencies.

(d) Evaluate the impact on performance of thermally induced bowing or of other distortions.

(e) Perform exploratory tests of local blow blockages.

(f) Validate and confirm existing thermo-hydraulic correlations.

In addition, the CFTL program will partake in the development of thermo-hydraulic correlations and their confirmation particularly in the areas of:

(g) Low flow, i.e , transition flow and laminar flow.

(h) Transients. These include power, flow, and geometrical configuration transients.

(i) Skew power distributions across the bundle.

(j) Depressurization transients including the design basis depressurization accident simulation (DBDA).

To support the CFTL mission of design and code verification and licensing support, the CFTL utilizes actual GCFR conditions of helium coolant pressure (0.1 - 10.6 MPa), temperature (to clad melting) flow (up to 3 kg/s) and helium impurities. A full-size blanket bundle can be accommodated in the CFTL. To enable fuel assembly conditions extrapolation to the full size of 271 rods, a series of bundles of 37, 61, and 91 fuel rod simulators is planned. The large bundles are necessary to allow the extrapolations. It was determined (Ref. 9) that the wall effects penetrate approximately two rows inward from the duct, hence a 91-rod bundle will have a 37-rod core unperturbed by the duct wall. The bundles will have prototypical GCFR dimensions, and the blanket bundle is prototypical start of the power source.

Thus, the CFTL provides another essential link in the development of thermohydraulic analytical capability for the GCFR. The CFTL is emphasizing the confirmation of earlier basic information; the scale-up leading to reliable extrapolations to full-size GCFR assemblies; the integration of various effects; the dimensional prototypicality; the augmentation of basic information primarily in low flow regimes; the information needed to analyze transients including depressurizations, the confirmed accuracy and systematic approach required to support licensing. The CFTL has the potential for testing special conditions if such will become necessary, however, none are presently planned.

3.2 BENCHMARK PROGRAM

Benchmark calculations program was proposed during a joint meeting between EIR, GA, and KfK in 1976. The purpose of this program is to improve the thermal-hydraulic correlations and calculational techniques used for GCFR analysis. The benchmark meetings held so far, the tests analyzed, and main conclusions drawn are summarized in Table 4. Since the Third Benchmark meeting, United Kingdom Atomic Energy Authority (UKAEA) and Central Electricity Board (CEGB) of UK have actively participated in the benchmark calculations using their own codes (Refs. 39-40).

The GCFR thermal-hydraulic benchmark calculations have lead to considerable improvement in the steady state codes used for the analysis and will result in preliminary validation of the codes for all flow conditions.

3.3 ACCIDENT CONDITIONS TEST

The tests described in previous sections are to obtain the basic correlations and to obtain sufficient data to verify steady state the subchannel analysis codes. In addition, other tests are planned for verification of transient accident analysis codes. These tests are discussed in detail in other papers at this meeting. The tests are described here in brief for completeness.

3.3.1 SMART TESTS

These tests were conducted at the Steel Melting and Reduction Test (SMART) facility at the Los Alamos Scientific Laboratory (LASL) (Ref. 10). The test uses full length rods in 37-rod bundle. The tests simulate the event sequence which follows a total loss of flow with SCRAM in the GCFR. The test results (Ref. 10) were used to develop an analytical model to describe the natural convection cooling developing within the fuel assembly when all forced flow is lost.

3.3.2 DEPRESSURIZED ACCIDENT CONDITION TEST

The objective of the Depressurization Accident Conditions Test (DACT) is to obtain experimental data for simulation of GCFR fuel assembly cooling under conditions characteristic of Design Basis Depressurization Accident (DBDA) (Ref. 11). The DACT test program will be conducted at LASL as part of the low power safety experiment program. It will use the same basic test rig and instrumentation that are used for the SMART.

3.3.3 NATURAL CIRCULATION TESTS

Natural circulation tests using a closed high-pressure helium loop with electrically heated GCFR fuel rods as a heat source are scheduled for the second quarter of 1980 (Ref. 12). The objective of the tests is to measure steady state and transient helium flow rate and fuel cladding temperatures under conditions similar to those encountered under natural circulation conditions in the GCFR. The test will also be used to identify experimental limitations and future test requirements and to help plan the system scale model tests that are planned as part of the natural circulation verification plan. The test results will be compared to analytical results predicted by a detailed RATSAM model of the test.

The primary components of the test loop will consist of 37 electrically heated rods, an internally insulated test vessel, an elevated water-cooled heat exchanger, connecting piping and a quick opening and closing check valve in the cold leg. A combination of power levels and pressures will be used to model a loss-of-coolant-circulation-pow[illegible]ident. The results will be used to verify the methods used to analyze [illegible]ural circulation and to plan future tests.

SUMMARY

The GCFR thermohydraulic development program is an international co-operative program. Adequate experimental facilities are available to generate base data and confirmatory information as needed for the GCFR. Testing performed supplied the data to support the analytical program and to provide the empirical correlations related to single-rod roughened surfaces and to clusters of rods under steady state conditions. Experiments in progress extend the data to transition flows and to laminar steady state flows. Planned experiments will cover the areas of transient flows, depressurizations, special conditions and combined effects.

The parallel analytical effort was successful in establishing parametric correlations of heat transfer and pressure drops for roughened surfaces and to account for impacts of spacers and duct walls. Various computer codes were developed or adapted for GCFR use. Improved and refined correlations and methods are being developed.

The interprogrammatic link between the experiments and the analytical development is provided by a series of systematic benchmark meetings. The benchmark calculations and meetings furnish the means of mutual support in analytical development, checking and cross checking of experimental results and concentration on areas of interest and concern, as well as channelling and directing the GCFR thermohydraulic development effort.

The program has been successful in advancing the understanding and calculational ability of thermal and fluid flow relations in bundles of rods with roughened surfaces at steady state to fill the needs of the GCFR. The future plans promise to provide the additional calculational ability to cover the needs of the GCFR program in the entire area of thermal and fluid flow. As a side benefit, it was already shown that a GCFR assembly can perform adequately as required by the design under normal operating conditions.

TABLE 1

THERMAL-HYDRAULIC EXPERIMENTAL PROGRAMS
FOR GCFR CORE ASSEMBLIES

INSTITUTE	PROGRAM	OBJECTIVES	REFERENCES
EIR	SINGLE ROD, SPACER, MIXING AND BUNDLES	BASIC CORRELATIONS, CODE DEVELOPMENT	3, 13 to 24
KfK	SINGLE ROD, SPACER, AND BUNDLES	BASIC CORRELATIONS, CODE DEVELOPMENT	4, 25 to 32
GA	INLET NOZZLE	DESIGN VERIFICATION	8
UCSB	WIRE-WRAPPED BUNDLES, FLOW-MIXING VANES	VERIFICATION OF EXISTING CORRELATIONS, MIXING DATA	5
MIT	ROUGHENED ROD BUNDLE	CODE DEVELOPMENT	6
UM	ROUGHENED PLATES	ROUGHNESS DESIGN IMPROVEMENT	7
ORNL	ROUGH ROD BUNDLE, WIRE-WRAP BUNDLE	CODE AND ASSEMBLY DESIGN VALIDATION	9
LASL	ACCIDENT TESTS	DYNAMIC SYSTEM BEHAVIOR, ESTABLISHMENT OF CODE VALIDATION TESTS	10, 11, 12

TABLE 2
SPACER TESTS

Type of Spacer	Fluid	No. of Rod	Rod Surface	Institute	Ref.
Regular hex	air	37	Smooth	EIR	15
Regular hex	water	169	Smooth	KFK	27,28
Rhombus	water	37	Smooth	KFK	27
Regular hex	air	61	Smooth	EIR	16
Modified hex	air	37	Smooth/Rough	EIR	17,18
Regular hex	water	12	Rough	KFK	29
Rhombic	air	37	Smooth/Rough	EIR	19

Table 3. Summary of GCFR Thermal-Hydraulic Bundle Tests

TEST	LABORATORY	COOLANT	NUMBER OF RODS	TYPE OF BUNDLE	STATUS (START DATE)
19 Rod	KfK	Helium	19	rough/smooth rods, flat duct, grid spacers	Completed
BR-2	KfK	Helium	12	rough/smooth rods, scalloped ducts, grid spacers	Completed
19-Rods With 3-D Roughness	KfK	Helium and N_2	19	rough/smooth rods, 3-D roughness, grid spacers, flat duct	(1980)
AGATHE-I	EIR	CO_2	37	rough/smooth rods, scalloped duct, grid spacers	Completed
AGATHE-II	EIR	CO_2	37	rough/smooth rods flat duct, corner support rods	(1980)
AGATHE-III	EIR	CO_2	37	rough rods, interior support rods	(1981)
37 Rod Test	MIT	Water	37	rough/smooth rods, grid spacers	Completed
61 Rod Wire-Wrapped	UCSB	Water	61	wire-wrapped, smooth	Completed
Mixing Vane	UCSB	Water	37	rough/smooth rods, grid spacers with mixing vanes	(1980)
CFTL	ORNL	Helium	37,61,91	(i) rough/smooth rods, flat duct (ii) wire-wrapped bundle	(1981)

Table 4. Summary of Benchmark Activity

BM	BUNDLE ANALYZED	TEST CONDITIONS	PARTICIPANTS IN CALCULATIONS	MAIN CONCLUSIONS
1	19 Rod (Helium)	• Turbulent • Laminar	EIR, GA, KfK	• Wall channel division
2	DR-2 (Helium	• Turbulent • Transition	EIR, GA, KfK	• Need to analyze different bundles
3	37 Rod AGATHE-I (CO_2)	• Turbulent • Transition	CEGB, EIR, GA, KfK, UKAEA	• Conduction heat transfer
4	37 Rod AGATHE-I (CO_2)	• Turbulent • Transition • Laminar • Turbulent with power tilt	CEGB, EIR, GA KfK, UKAEA	• Radiation heat transfer
5	37 Rod AGATHE-I (CO_2)	• Laminar • Laminar with power tilt • Turbulent with two rows heated	CEGB, EIR, GA, KfK, UKAEA	• Duct conduction • Heat losses • Natural Convection effects

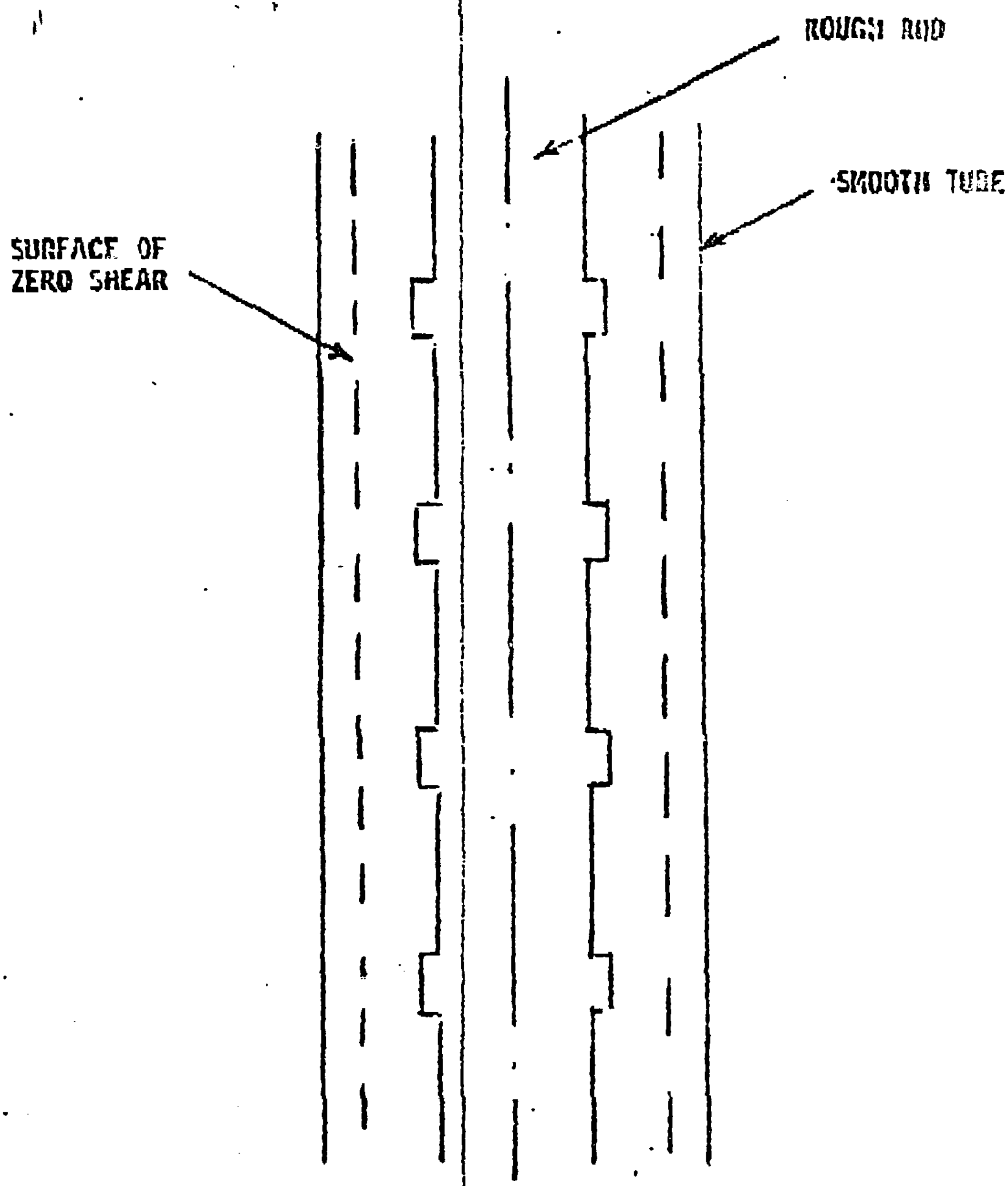

Fig. 1. Configuration for Single Rod Tests

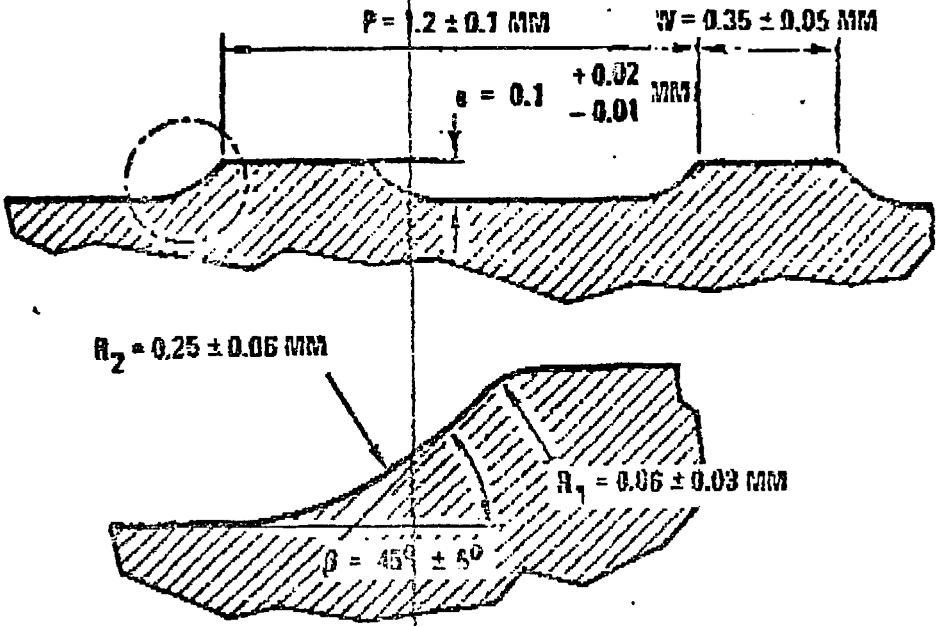

Fig. 2. Roughness configuration for AGATHE experiments and GCFR. The rib height of 3-loop GCFR is 0.13 mm (Ref. 14).

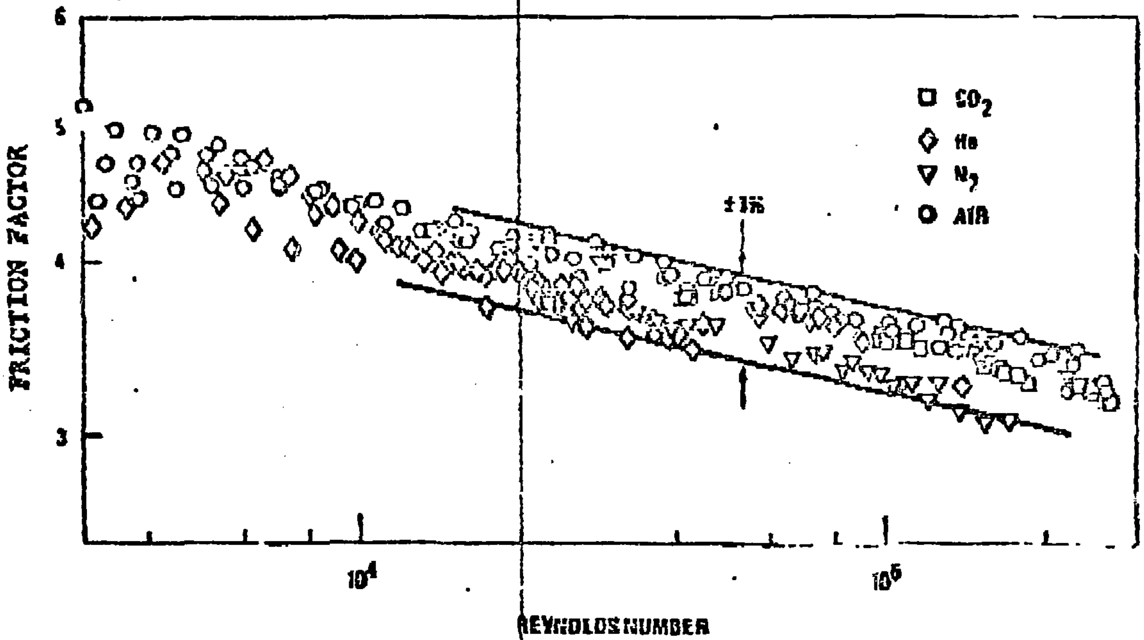

Fig. 3. Benchmark experiment comparison of measured global friction factors (Ref. 26).

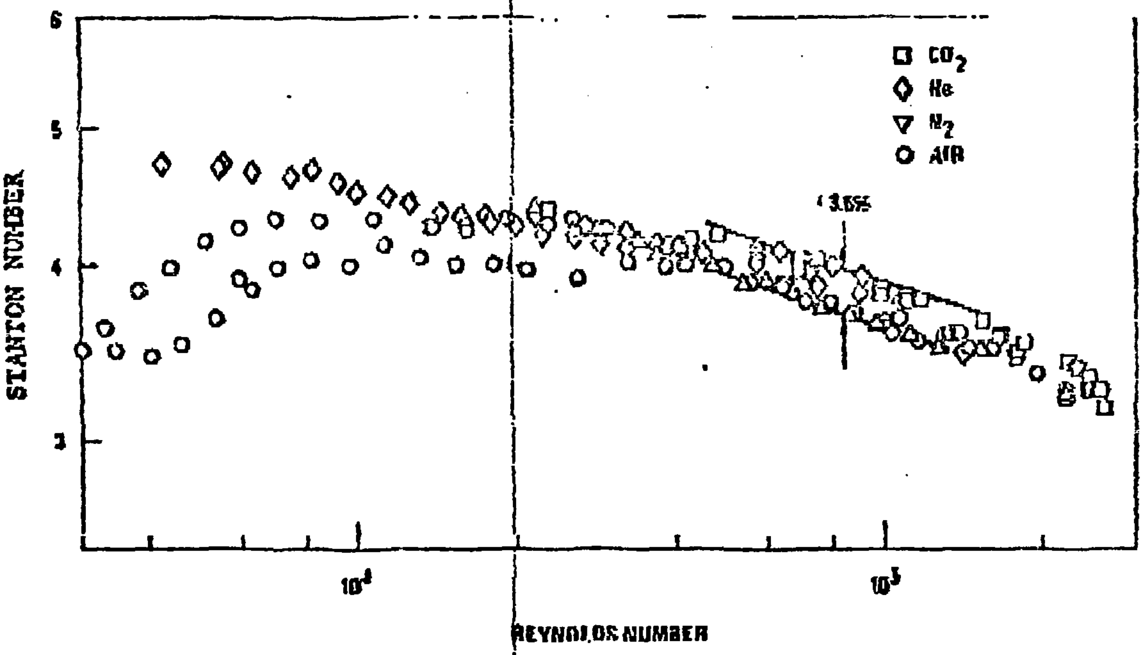

Fig. 4. Benchmark Experiment comparison of measured global Stanton numbers (Ref. 26).

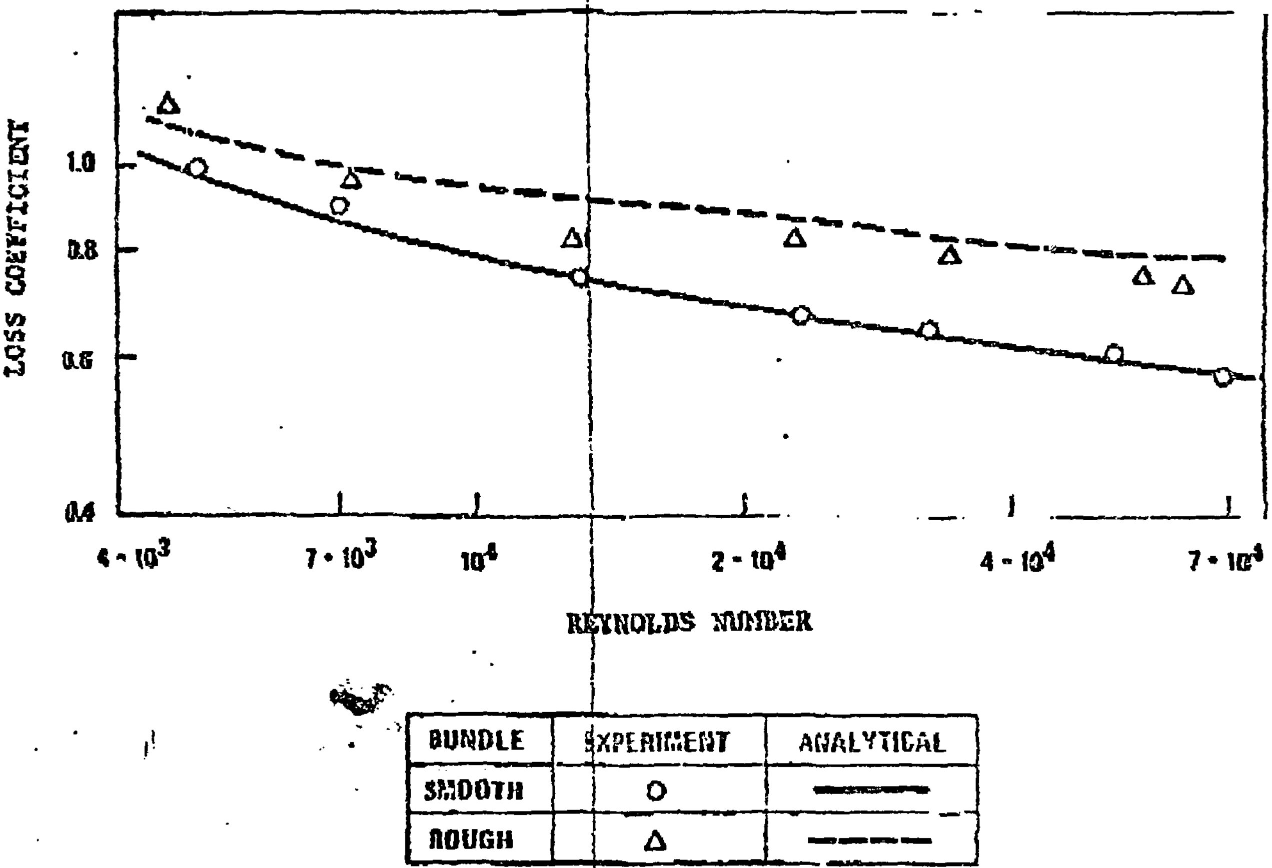

Fig. 5. Comparison of analytical results with experimental points for GCFR type spacers (Ref. 20).

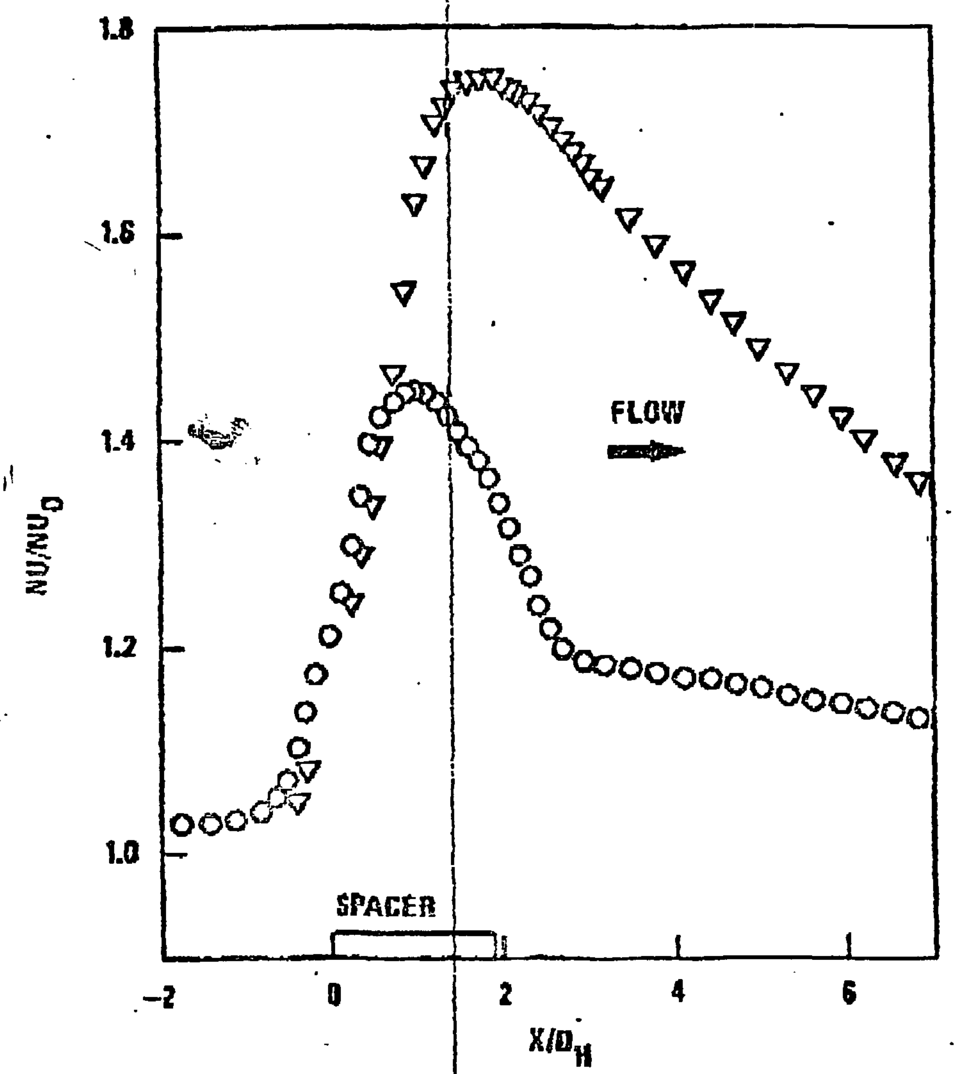

Fig. 6. Axial distribution of the Nusselt numbers measured between the ribs of the spacers ∇ smooth; ○ rough (Ref. 30).

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