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International Agreement Report

Assessment of RELAP5/MOD3.2 for Thermohydraulic Processes in Heated Rod Bundles with Tight Lattice at CKTI Test Facility

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ABSTRACT

The assessment of RELAP5/MOD3.2 for two-phase hydrodynamics and heat transfer processes in the rod bundle model with tight lattice are presented. This experiments have been carried out at the bundle with non-standard geometrical characteristics - close packed assembly and small hydraulic diameters. The investigations have been carried out at the following range of parameters: pressures P = 0.23-2.0 MPa, inlet water flowrate from zero up to G=17-18.3 kg/c, heat fluxes q – up to 0.96 kW/m^2 and void fractions $\alpha = 0.03 - 0.89$.

RELAP5/MOD3.2 assessment for processes at steady state conditions at small or zero flowrates at the inlet of the tube bundle showed that for such processes code gives rather good results. The comparison of computed and experimental results for process of boil-off and reflooding shows that there is a good coordination between computed and experimental values between temperatures of pipe bundle walls for upper part of the bundle. For lower part of the bundle there are some discrepancies between computed and experimental values of temperature, the later being some lower than experimental ones. The calculated values of shroud temperature were rather less than experimental ones.

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EXECUTIVE SUMMARY

This report presents the results of RELAP5/MOD3.2 assessment in the prediction of two-phase hydrodynamics and heat transfer in rod bundle model with tight lattice. The experiments have been carried out at the CKTI (St' Petersburg) test facility. The peculiarities of these researches were the non-standard geometrical characteristics of the 55-rod bundle - close packed assembly and small hydraulic diameters, and also the parameters - small flowrates (down to zero) and low pressure (from 0.23 up to 2.0 MPa).

The assessment of RELAP5/MOD3.2 code was done for two cases: for steady state conditions at small or zero flowrates at the inlet of the rod bundle and for boil-off and reflooding processes. The comparison of calculated results with experimental ones shows that there was a good coordination between computed and experimental values of void fractions and bundle wall temperatures for almost all the tests.

1. INTRODUCTION

RELAP5/MOD3.2 assessments for low velocity two-phase flow hydrodynamics and heat transfer processes in the rod bundle model are not numerous. All the more such assessments are interesting for non-standard geometry as for rod bundles with tight lattice. Such experiments have been carried out at CKTI test facility (St' Petersburg). The peculiarities of these researches were the non-standard geometrical characteristics of the bundle - close packed assembly and small hydraulic diameters, and also the parameters - small flowrates (down to zero) and low pressure (from 0.23 up to 2.0 MPa).

The assessment of RELAP5/MOD3.2 code was done for two cases: for steady state conditions at small or zero flowrates at the inlet of the rod bundle and for boil-off and reflooding processes.

2. EXPERIMENTAL FACILITY DESCRIPTION

CKTI test facility (Fig.1) consists of test section, system of preparing of flow with needed parameters and measurement system.

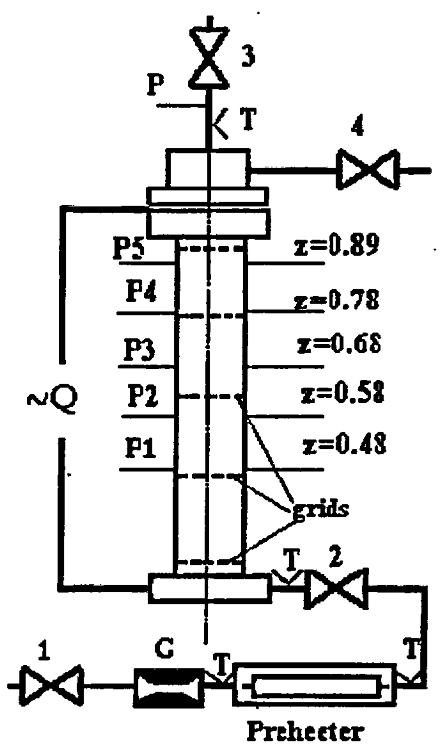

Fig. 1 Scheme of CKTI test facility

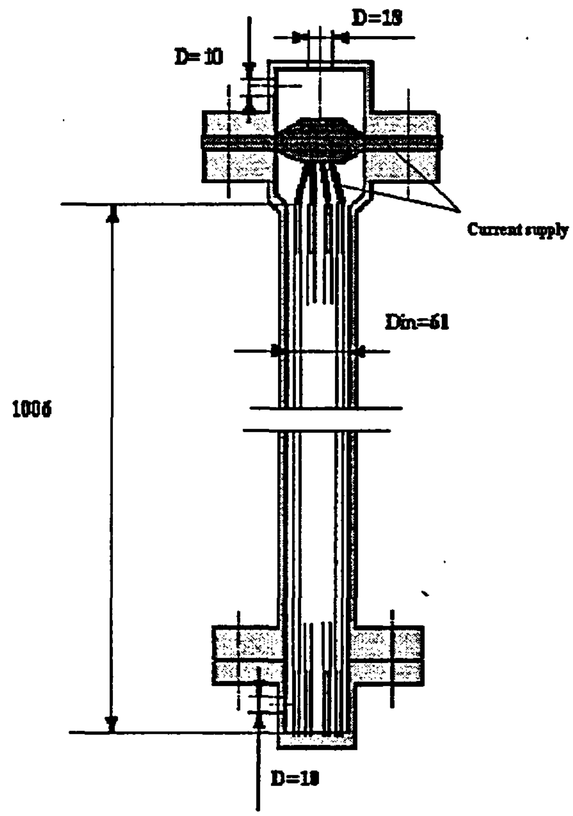

Fig. 2 Test section

Test section is a 55-pipes bundle with 6x1 mm diameter stainless steal tubes with heated length 1006mm (Fig. 2). 6 corner pipes were made from insulator (Fig. 3). Pipe bundle was placed into the shroud 61 x 1 mm. Pipe bundle and shroud were heated with alternating current. There were five grids along the bundle. First grid was near the bottom and the distance between them was 200 mm. The pitch of the bundle equals to 7.35 mm. The corner rods were made from insulator 5mm diameter and they were unheated (Fig. 3). All the elements of the model excluding the corner rods and copper current supply were made of stainless steel 12X18H10T. The bottom part of the model had the flow inlet orifice 10mm diameter and the upper one had two ones: axial orifice 18mm diameter for flow outlet and side one 10mm diameter for flow inlet for tests without bottom inlet flow. Flow control for different tests series was made with using valves 1 - 4 (Fig.1).

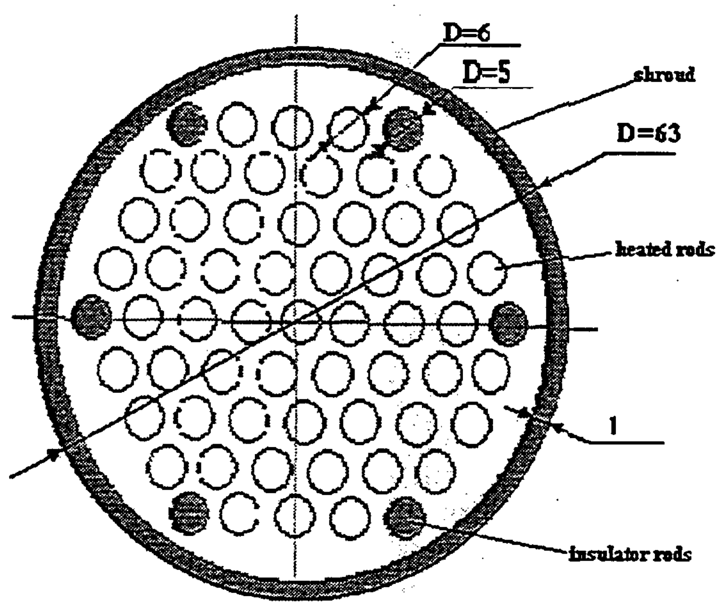

Fig. 3 Cross section of rod bundle

Geometrical and hydraulic characteristics of tube bundle are presented in Table 1.

Table 1. Characteristics of test section

Element	Hydraulic diameter, mm	Length, mm	Area, mm^2	Flow losses
Bundle inlet	10	170	78.5	365
Tube bundle	3.77	1006	1249	13.04
Bundle outlet	20	21	2515	0.155

Flow area and flow losses of each row of grid equal to 1072 mm^2 and 0.49 accordingly.

Upper plenum volume between bundle outlet and outlet orifice equals to 0.6×10^{-3} m^3.

There were the preheater before the bundle inlet – electrical heated tube 22x3mm diameter with length 3m inclined at 7° to horizon.

During the experiment the following parameters were measured:

- Pressure in the top of the model,
- Pressure differences along the channel at locations shown at Fig. 1,
- Flow temperatures at the bundle inlet and outlet and before the preheater,
- Inner heated tubes walls temperatures (54 thermocouples), the axial distance between the thermocouples were 20-30mm,

- Mass flowrate at the bundle inlet,
- Electrical power which is a sum of the bundle and shroud power and it was divided between them as 0.8 : 0.2.

Void fraction was determined as an average value between two pressure drop measurement locations. The accuracy of this method at low flowrates is rather small and equals to $\Delta\alpha = (2 - 6)\times10^{-2}$.

3. RESULTS OF THE EXPERIMENTS

First series of experiments was devoted to investigation of void fraction at low upward flowrates. The parameters of the investigations were the following: pressures P = 0.23-2.0 MPa, inlet water flowrate G=17-18.3 kg/c, heat fluxes q – up to 0.96 kW/m^2 and void fractions α = 0.03 –0.89.

The results of this experiments are shown in Table 2, in which T is water temperature at the preheater inlet, G – water flowrate, Q – preheater or bundle power, α - void fraction and $J_g = \alpha V_g$ – superficial vapor velocity.

Table 2. Experimental data for low flowrates

Test N	T inlet, C	G, kg/s	P, MPa	Q preheater, kW	Q bundle, kW	α_1/α_2 experiment	$(J_g)_1/(J_g)_2$ experiment
6	95	17.9	0.23	7.55	1.04	0.62/0.52	1.4/1.33
7	95	18	0.23	7.55	2.34	0.66/0.55	1.7/1.6
8	95	18.4	0.23	7.55	3.9	0.7/0.6	2.1/1.9
9	93.5	17.9	0.23	7.55	6.5	0.75/0.69	2.75/2.38
10	93.5	17.7	0.23	7.55	9.15	0.82/0.76	3.3/2.87
11	93.5	18	0.23	7.55	12.4	0.9/0.82	4.16/3.6
12	93.5	18	0.23	7.55	14.9	0.94/0.84	4.78/4
13	93.5	17.8	0.23	7.55	6.32	0.71/0.65	2.69/2.33
21	128.5	17.6	0.56	10.75	1.08	0.56/0.57	1.036/1.009
22	127.5	16.9	0.54	10.75	2.48	0.65/0.63	1.274/1.217
23	126.5	17.3	0.54	10.75	4.35	0.67/0.64	1.483/1.371
24	126.5	17.3	0.53	10.75	6.74	0.7/0.67	1.773/1.6
25	125	17.15	0.53	10.75	9.3	0.77/0.74	2.053/1.823
26	125	17.3	0.51	10.75	12.3	0.81/0.76	2.533/2.323
27	125	18.6	0.50	10.75	15	0.82/0.76	2.843/2.433
28	125	17.6	0.49	10.75	9.1	0.74/0.69	2.16/1.903
55	128.5	17	2.0	16.13	1.17	0.51/0.47	0.405/0.405
56	128.5	17.1	2.0	16.13	2.62	0.53/0.5	0.415/0/412
57	127.5	17.6	1.98	16.13	3.7	0.51/0.64	0.5/0.48
58	127.5	17	2.02	16.13	7.38	-/0.53	-/0.58
59	127.5	17.1	2.0	16.13	9.9	-/0.51	-/0.64
60	127.5	17	2.0	16.13	13.5	0.67/0.6	0.84/0.74
61	127.5	17.1	2.0	16.13	14.7	0.69.0.66	0.88/0.77
62	126	17	1.8	16.13	5.86	0.56/0.54	0.605/0.56

Indexes 1 and 2 concern to bundle locations with z=0.78-0.98 and z=0.58-0.78 accordingly from the bottom of the model. $Q_{preheater}$ means the power of preheater before the bundle.

The second series of experiments have been carried out with closed at the bottom bundle and at pressure P =1.28 MPa. The results of these experiments are presented in Table 3.

Table 3. Experimental data for closed inlet

Test number	P, MPa	Q, kW	α_1/α_2 experiment	$(Jg)_1/(Jg)_2$ experiment
12	1.28	5.1	0.39/0.29	0.203/0.146
13	1.28	5.3	0.4/ -	0.215/0.154
14	1.28	4.6	0.34/0.26	0.183/0.131
15	1.28	4.9	0.4/0.31	0.198/0.143
16	1.28	6.6	0.485/ -	0.28/0.211
17	1.32	6.6	0.43/0.37	0.28/0.211
18	1.32	4.75	- /0.26	0.183/0.134
19	1.32	9.3	0.53/0.44	0.422/0.317

The third series of experiments is presented with only one test in which it was investigated the behavior of bundle model in modes of partial uncovering and reflooding. This test was carried out at the following initial parameters: pressure P=1.32 MPa, test section power Q=9.3 kW, inlet flowrate at reflooding G=9.8g/s, inlet water temperature $T_{in} = T_s - 1$ K, where T_s – saturation temperature.

4. NODALIZATION SCHEME

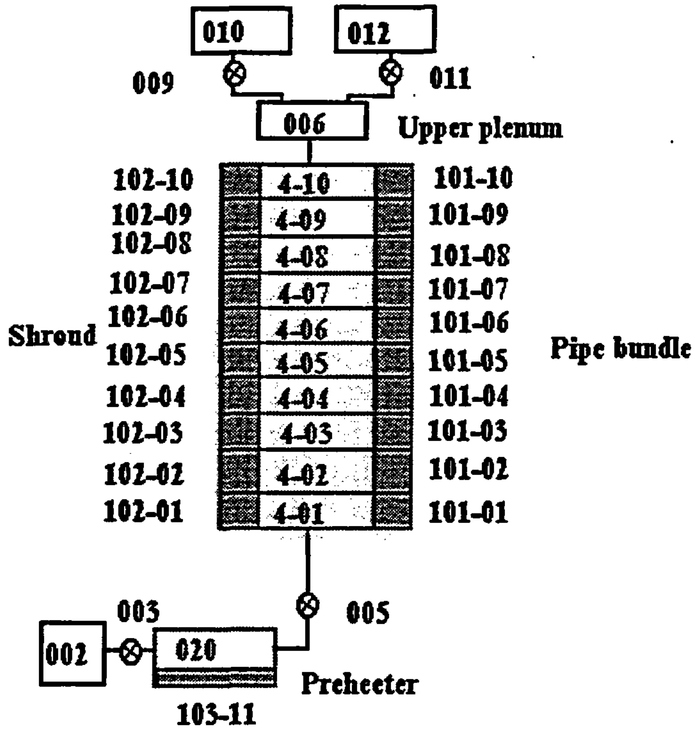

Fig. 4 Nodalization scheme of test facility

The nodalization scheme of test facility is shown in Fig. 4. It consists of element 004 "pipe" divided into 10 subvolumes with two heat structures connected to it: 101 – modeling 55 heated tubes and 102 – modeling the heated shroud. Heat losses heat flux is determined on the outer surface of the shroud. Element 008 models the volume placed above the bundle and it is connected to the volume 010 (through the "sngljun") in which were set the conditions of saturated vapor. For the tests without inlet flow volume 010 was connected with volume 012 in which were set the conditions of saturated water. Element 020 models the preheater and the parameters of flow at its conditions were set in "tmdpvol" 002 and "tmdpjun" 003. In boiloff test elements 002 and 003 were connected with pipe 004 (without preheater).

Heat losses on outer surface of preheater and shroud were set according to experimental tare as:

Q = 5 (T-293) W – for preheater,

Q = 13.5(T-293) W – for shroud, where T – metal surface temperature (K).

5. RESULTS OF CALCULATIONS FOR STEADY STATE CONDITIONS

Results of calculations and experimental ones for tests with low inlet flowrate and for pressures P=0.23-0.56 MPa are presented in Table 4 and in Fig. 5. This figure shows the dependency of $\alpha_{experiment.} = f\ (Jg_{\ experiment.})$ and $\alpha_{calculated.} = f\ (Jg_{\ calculated.})$, where $Jg = \alpha V_g$ – superficial vapor velocity, α - void fraction. This figure shows the results of experiments and calculations for tests without inlet flowrate also, which were conducted at some higher pressure P = 1.32 MPa. One can see that the results of calculations are closed to experimental ones at Jg < 2 m/s and they are some lower at velocities larger than 2.5 m/s.

Table 4. Results of calculations and experimental ones for low flowrates

Test number	α_1/α_2 RELAP	α_1/α_2 experiment	$(Jg)_1/(Jg)_2$ RELAP	$(Jg)_1/(Jg)_2$ experiment
6	0.581/0.583	0.62/0.52	2.49/2.51	1.4/1.33
7	0.607/0.602	0.66/0.55	2.92/2.82	1.7/1.6
8	0.627/0.624	0.7/0.6	3.51/3.28	2.1/1.9
9	0.657/0.647	0.75/0.69	4.56/4.1	2.75/2.38
10	0.721/0.667	0.82/0.76	5.9/5.27	3.3/2.87
11	0.825/0.662	0.9/0.82	5.88/5.91	4.16/3.6
12	0.82/0.64	0.94/0.84	7.3/6.87	4.78/4
13	0.66/0.65	0.71/0.65	4.5/4.06	2.69/2.33
21	0.547/.55	0.56/0.57	1.98/2.0	1.036/1.009
22	0.577/0.574	0.65/0.63	2.31/2.28	1.274/1.217
23	0.606/0.596	0.67/0.64	2.7/2.61	1.483/1.371
24	0.645/0.623	0.7/0.67	3.18/3.0	1.773/1.6
25	0.678/0.651	0.77/0.74	3.25/3.14	2.053/1.823
26	0.663/0.651	0.81/0.76	4.43/3.97	2.533/2.323
27	0.674/0.662	0.82/0.76	5.03/4.45	2.843/2.433
28	0.652/0.64	0.74/0.69	3.95/3.62	2.16/1.903
55	0.3/0.35	0.51/0.47	0.9/0.93	0.405/0.405
56	0.338/0.381	0.53/0.5	0.99/.0.99	0.415/0/412
57	0.405/0.407	0.51/0.64	1.05/1.03	0.5/0.48
58	0.472/0.456	-/0.53	1.26/1.2	-/0.58
59	0.503/0.483	-/0.51	1.41/1.32	-/0.64
60	0.536/0.514	0.67/0.6	1.62/1.48	0.84/0.74
61	0.545/0.523	0.69.0.66	1.69/1.53	0.88/0.77
62	0.473/0.46	0.56/0.54	1.28/1.24	0.605/0.56

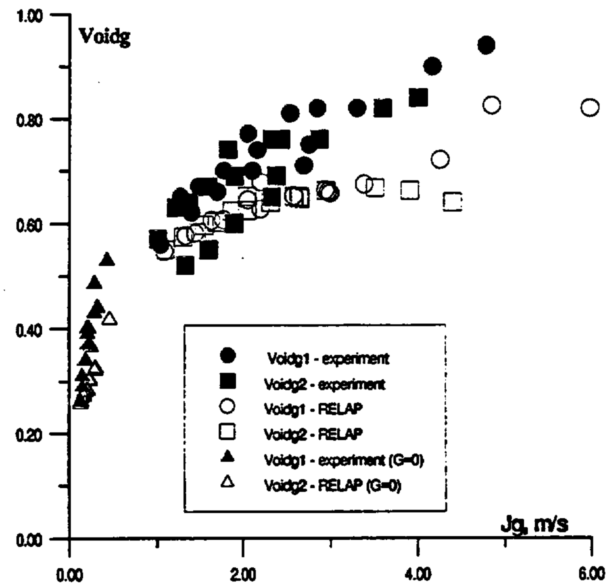

Fig. 5 Dependence of void fraction from superficial velocity for two levels for low and zero flowrates and low pressures

Figure 6 shows the results for larger pressures P = 2MPa. In this case the difference between experimental data and RELAP results are larger and RELAP void fractions are much lower than experimental values.

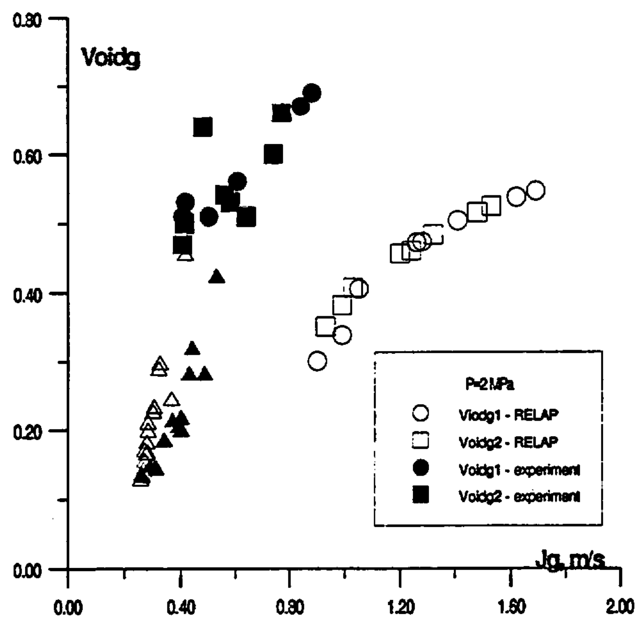

Fig. 6 Results of calculations and experimental ones for low flowrates and pressure 2 MPa

The results of some of this experiments in coordinates $\alpha=f(x)$, where x is equilibrium quality are presented in Figures 7 and 8.

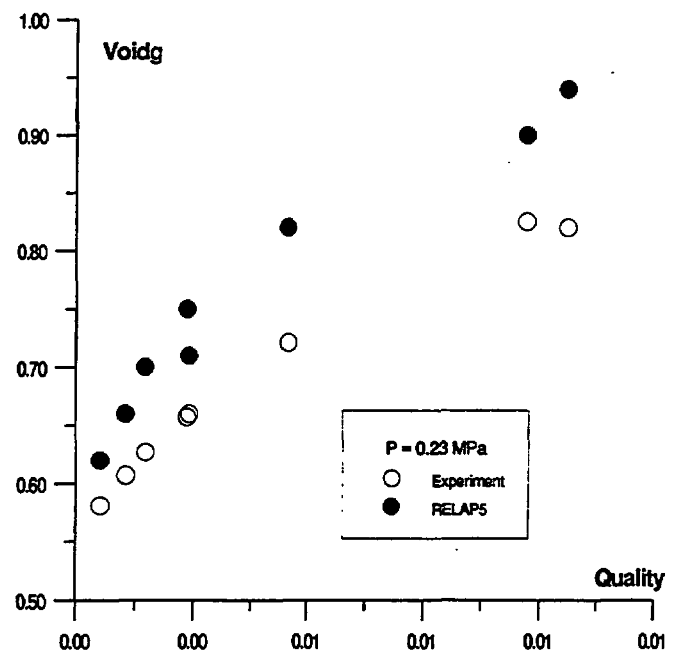

Fig. 7 Dependence of void fraction from equilibrium quality at P=0.23 MPa

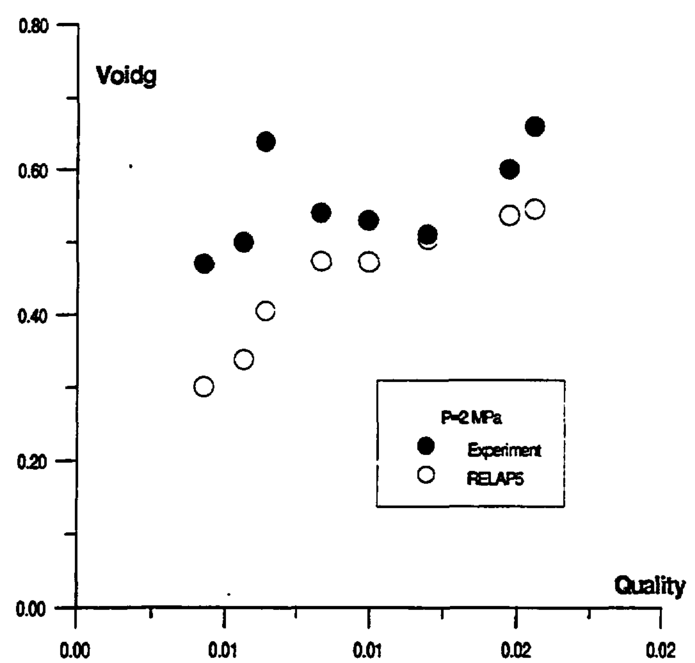

Fig. 8 Dependence of void fraction from equilibrium quality at P=2.0 MPa

The results for test without inlet flow (G=0) are presented in Fig. 9 and Table 5.

Table 5. Results of calculations and experimental ones for closed inlet

Test number	α_1/α_2 RELAP	α_1/α_2 experiment	$(Jg)_1/(Jg)_2$ RELAP	$(Jg)_1/(Jg')_2$ experiment.
12	0.283/0.271	0.39/0.29	0.197/0.153	0.203/0.146
13	0.283/0.28	0.4/-	0.2081/0.165	0.215/0.154
14	0.276/0.256	0.34/0.26	0.164/0.126	0.183/0.131
15	0.279/0.267	0.4/0.31	0.18/0.1407	0.198/0.143
16	0.325/0.304	0.485/-	0.295/0.23	0.28/0.211
17	0.321/0.301	0.43/0.37	0.287/0.223	0.28/0.211
18	0.271/0.261	-/0.26	0.169/0.132	0.183/0.134
19	0.416/0.366	0.53/0.44	0.453/0.242	0.422/0.317

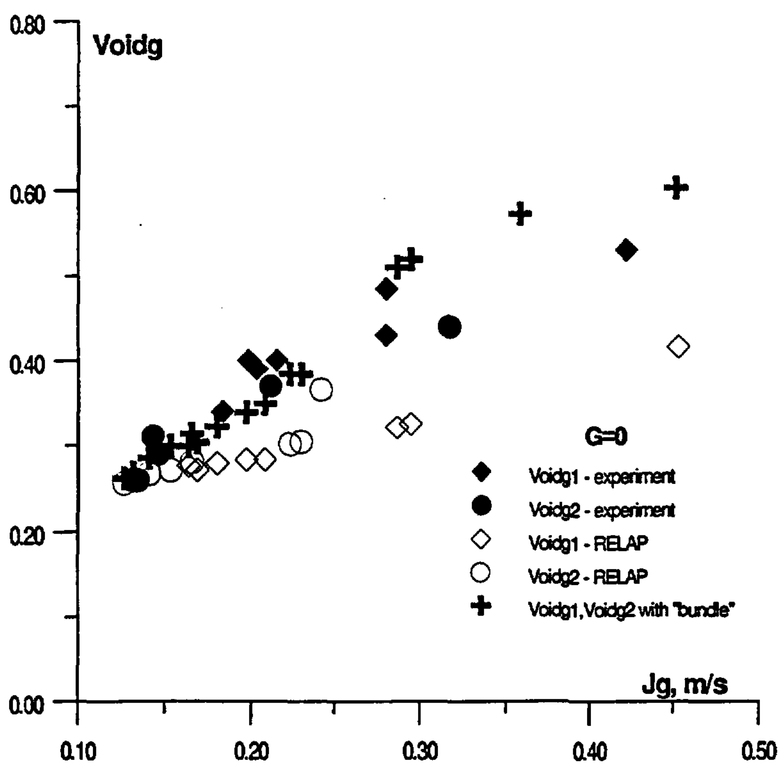

Fig. 9 Dependence of void fraction from superficial velocity for closed inlet

It is evident that practically in all cases the calculated values of void fraction are lower than experimental ones. It is clear that vapor drift calculated by RELAP is larger than in experiments especially at higher velocities.

The next series of calculations were made with the same nodalization scheme but with using option "bundle" in setting the geometry of "pipe" which models the pipe bundle. Switching of this option changes the model of vapor drift calculation.

Fig. 10 shows the RELAP and experimental data for low pressures and Fig. 11 for pressure 2 MPa. These data are shown in tables 6 and 7 also.

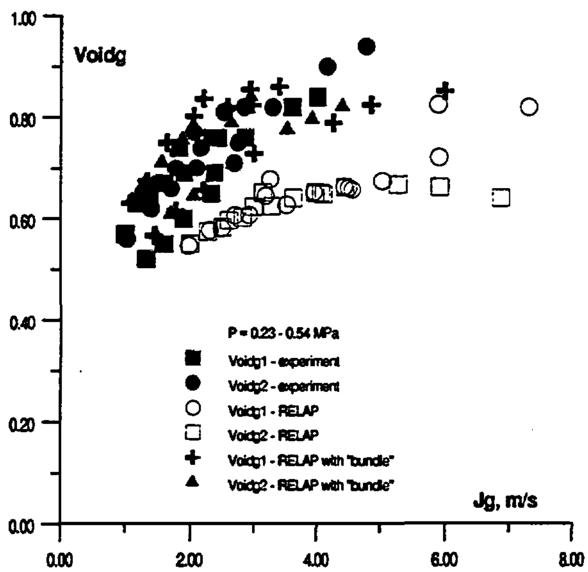

Fig. 10 Dependence of void fraction from superficial velocity at P = 0.23 –0.54 MPa

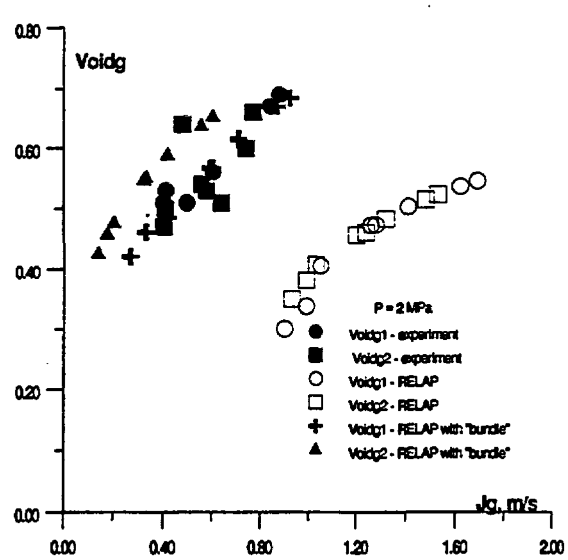

Fig. 11 Dependence of void fraction from superficial velocity at P=2.0 MPa for "bundle" option

It is evident that using of drift flux models developed with taking into account of specific character of two phase flow in rod bundles adjust with experimental data much better.

The similar results for case of zero inlet flow are presented in Fig. 12.

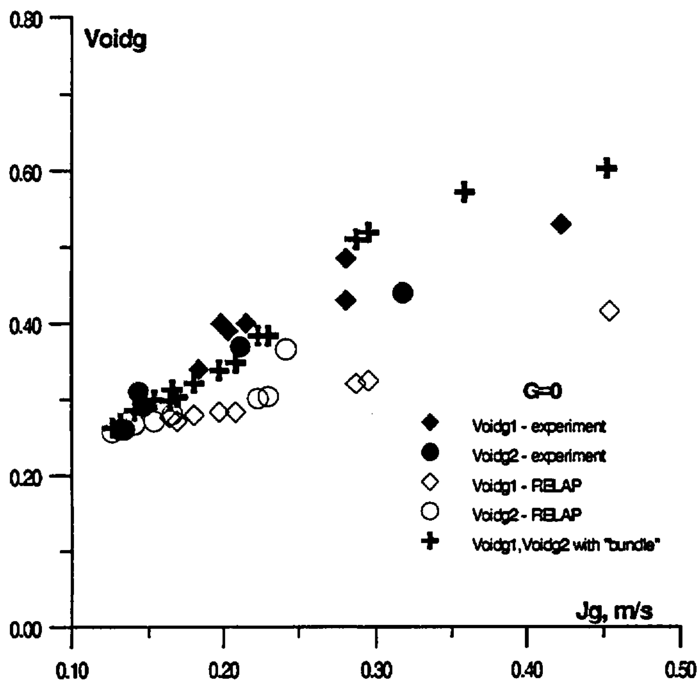

Fig. 12 Dependence of void fraction from superficial velocity at P=2.0 MPa for "bundle" option

It is evident that in this case the accordance between RELAP data and experimental ones with using "bundle" option is better also.

Table 6. Results of calculations and experimental ones for low flowrates ("bundle" option)

Test number	α_1/α_2 RELAP	α_1/α_2 experiment	$(Jg)_1/(Jg)_2$ RELAP	$(Jg)_1/(Jg)_2$ experiment
6	0.567/0.570	0.62/0.52	2.49/2.51	1.4/1.33
7	0.616/0.609	0.66/0.55	2.92/2.82	1.7/1.6
8	0.655/0.645	0.7/0.6	3.51/3.28	2.1/1.9
9	0.729/0.707	0.75/0.69	4.56/4.1	2.75/2.38
10	0.789/0.776	0.82/0.76	5.9/5.27	3.3/2.87
11	0.825/0.797	0.9/0.82	5.88/5.91	4.16/3.6
12	0.851/0.822	0.94/0.84	7.3/6.87	4.78/4
13	0.824/0.79	0.71/0.65	4.5/4.06	2.69/2.33
21	0.630/0.636	0.56/0.57	1.98/2.0	1.036/1.009
22	0.674/0.673	0.65/0.63	2.31/2.28	1.274/1.217
23	0.750/0.711	0.67/0.64	2.7/2.61	1.483/1.371
24	0.802/0.756	0.7/0.67	3.18/3.0	1.773/1.6
25	0.836/0.784	0.77/0.74	3.25/3.14	2.053/1.823
26	0.854/0.819	0.81/0.76	4.43/3.97	2.533/2.323
27	0.860/0.840	0.82/0.76	5.03/4.45	2.843/2.433
28	0.820/0.64	0.74/0.69	3.95/3.62	2.16/1.903
55	0.421/0.425	0.51/0.47	0.9/0.93	0.405/0.405
56	0.461/0.457	0.53/0.5	0.99/.0.99	0.415/0/412
57	0.485/0.476	0.51/0.64	1.05/1.03	0.5/0.48
58	0.567/0.546	-/0.53	1.26/1.2	-/0.58
59	0.615/0.588	-/0.51	1.41/1.32	-/0.64
60	0.67/0.637	0.67/0.6	1.62/1.48	0.84/0.74
61	0.685/0.652	0.69.0.66	1.69/1.53	0.88/0.77
62	0.567/0.55	0.56/0.54	1.28/1.24	0.605/0.56

Table 7. Results of calculations and experimental ones for closed inlet ("bundle" option)

Test number	α_1/α_2 RELAP	α_1/α_2 experiment	$(Jg)_1/(Jg)_2$ RELAP	$(Jg)_1/(Jg)_2$ experiment
12	0.339/0.299	0.39/0.29	0.203/0.146	0.203/0.146
13	0.349/0.313	0.4/-	0.215/0.154	0.215/0.154
14	0.298/0.262	0.34/0.26	0.183/0.131	0.183/0.131
15	0.322/0.285	0.4/0.31	0.198/0.143	0.198/0.143
16	0.519/0.384	0.485/-	0.280/0.211	0.28/0.211
17	0.510/0.384	0.43/0.37	0.280/0.211	0.28/0.211

18	0.303/0.268	-/0.26	0.183/0.134	0.183/0.134
19	0.603/0.572	0.53/0.44	0.422/0.317	0.422/0.317

6. RESULTS OF CALCULATIONS FOR BOILOFF TEST AND SENSITIVITY ANALYSIS

The initial conditions for this test is the same as for test N19 without water supply from the bottom of test section. An absence of inlet water flow leads to level decreasing in the upper plenum of test section. After some period of time the level reaches the upper part of heated pipes and zone of uncovered bundle increases and heatup of tubes begins. If temperature of pipe tube reaches 555 C^0 water supply into the bottom part of test section and reflooding process begins. The flowrate of water is G=9.8 kg/s and its temperature is $T_s - 1$ K, where T_s – is saturation temperature.

Fig. 13 shows the results of calculations and experimental ones for collapsed level in the test section. The calculations were made for two cases: with and without option "bundle". The initial values of level are different for these cases because of different void fraction distribution along the channel. However the time of maximal temperature reaching is almost the same for both cases. Physical level behavior determined as the time of wall temperature rising (or dropping at reflood stage) is shown in Fig. 14.

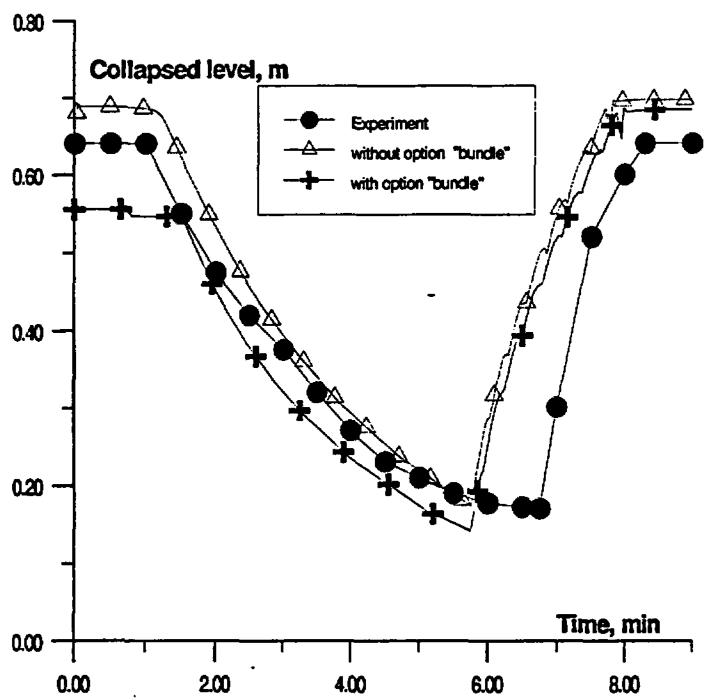

Fig. 13 Collapsed level behaviour

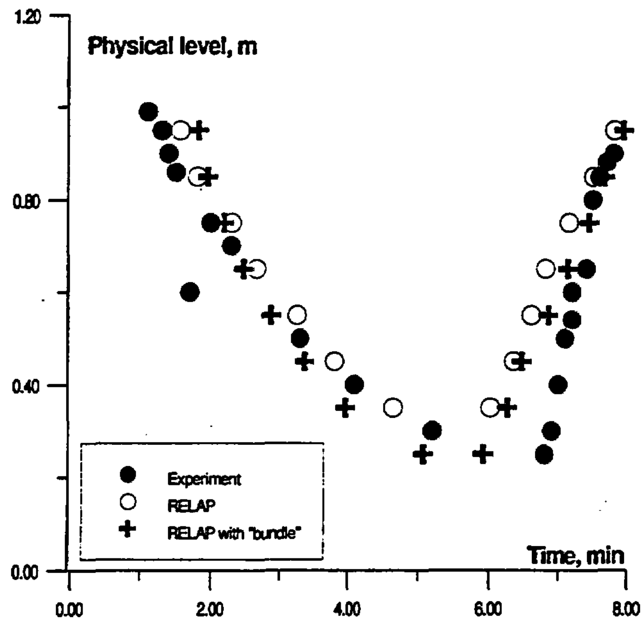

Fig. 14 Physical level behaviour

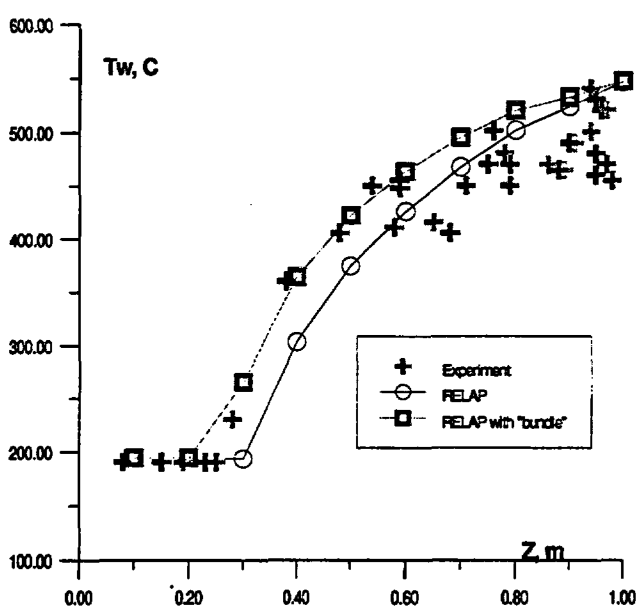

Fig. 15 Rods temperature distribution along the height before the reflooding stage

Fig. 16-20 show the behaviour of pipe bundle wall temperatures for different locations along the height. The calculated temperatures in the down part of uncovered zone are some lower than the experimental ones. The calculated temperatures in the upper part of uncovered zone are conversely higher than the experimental values that leads to more earlier attainment of maximal temperature and reflooding beginning. Figure 16 shows the experimental behaviour of wall temperature at Z=0.28 m and calculated one for two locations nearest to measurement point - for Z=0.25m and Z=0.35m. It is evident that calculated values are much higher than experimental one. For more higher locations the difference between experimental and computed values become smaller and for Z=0.95m (Fig. 20) the accordance between experimental and computed values becomes good enough for both cases – with using "bundle" option and without it.

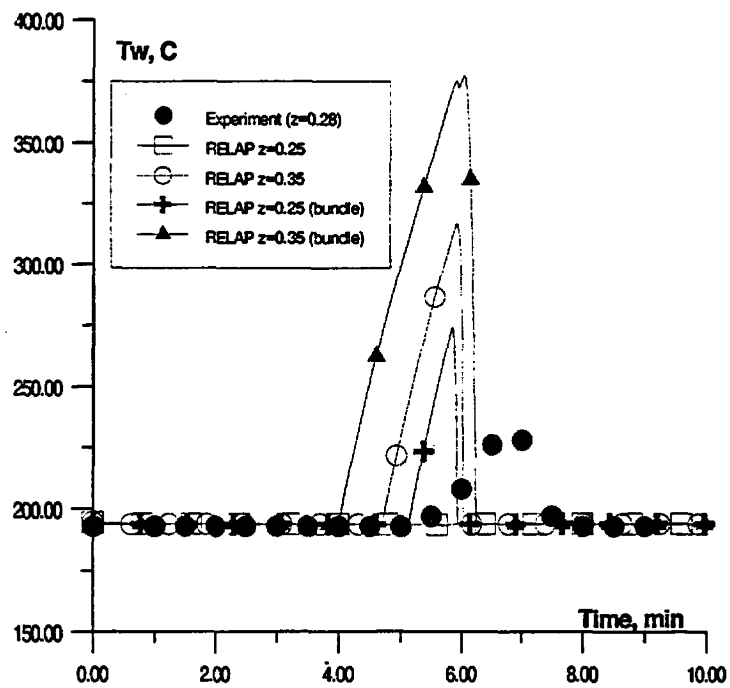

Fig. 16 Rod temperature behavior at z=0.28m

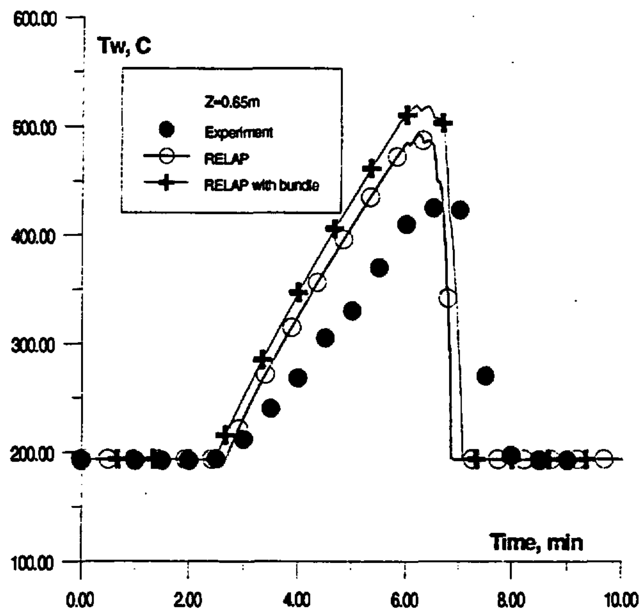

Fig. 17 Rod temperature behaviour at z=0.66m

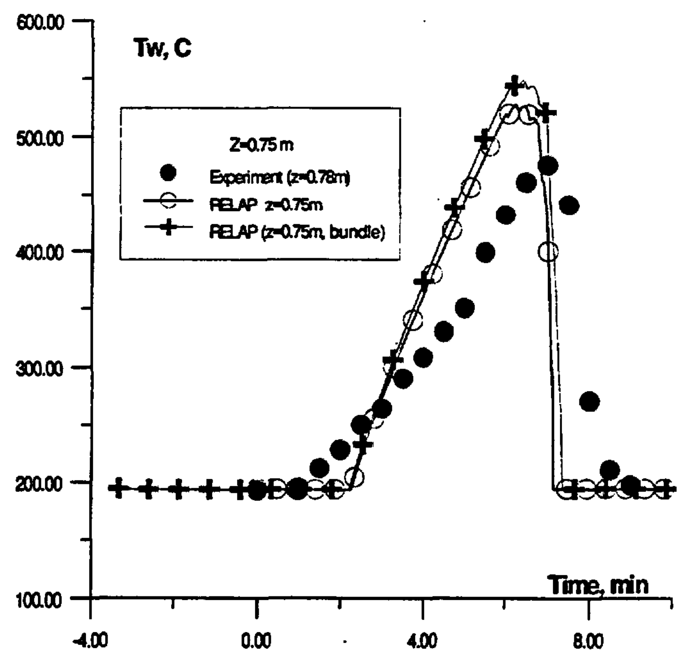

Fig. 18 Rod temperature behaviour at z=0.75m

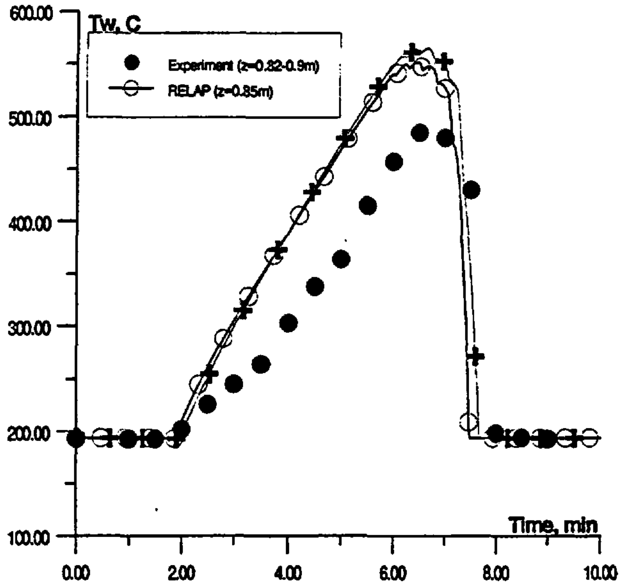

Fig. 19 Rod temperature behaviour at z=0.9m

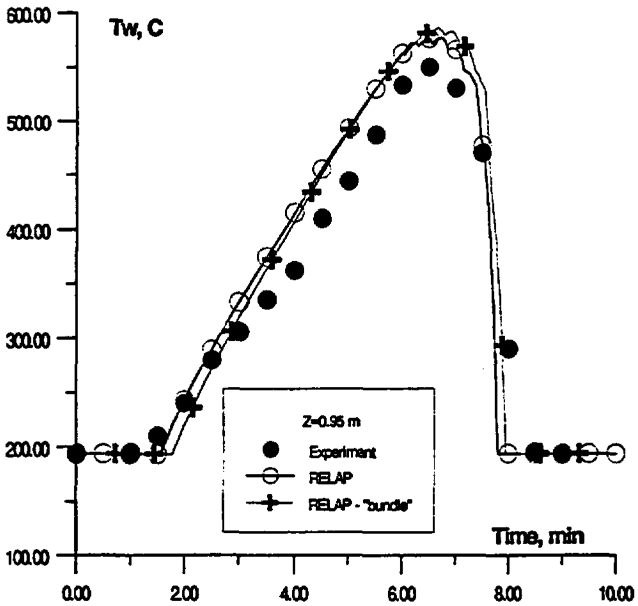

Fig. 20 Rod temperature behaviour at z=0.95m

During the test the upper part of the bundle becomes uncovered and heating of tubes walls change their electrical resistance and power distribution along the test section. Fig. 21 shows the results of calculations with taking into account the dependency of the stainless steel electrical resistance from temperature. One can see that the results for both cases are almost the same.

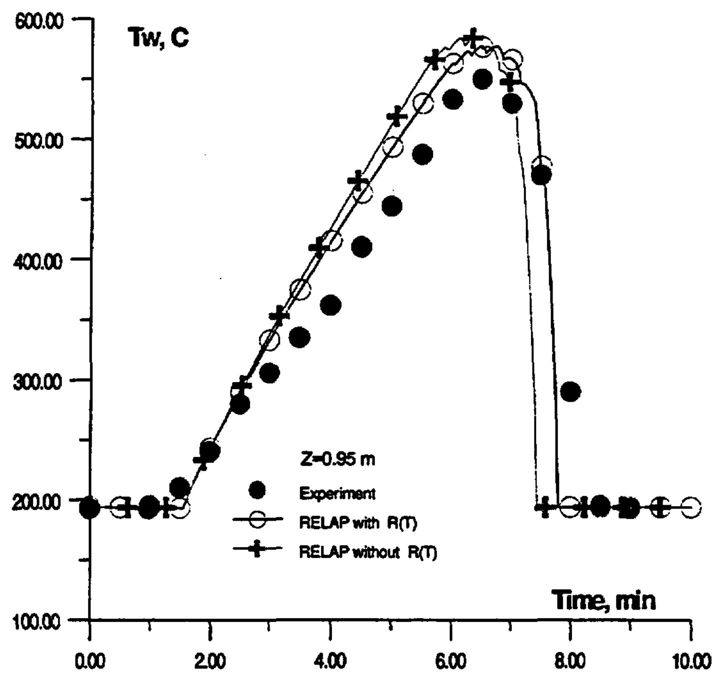

Fig. 21 Rod temperature behaviour at z=0.95m with taking into account rod electrical resistance dependency from temperature.

More important factor for parameters behaviour is the value of upper plenum volume. It's too difficult to obtain its value from the geometrical data. Fig. 22 shows the dependence of level behaviour from upper plenum volume. It is evident that V=0.0006 m^3 gives the best result for time of level drop beginning. So all of the calculations were made with this value.

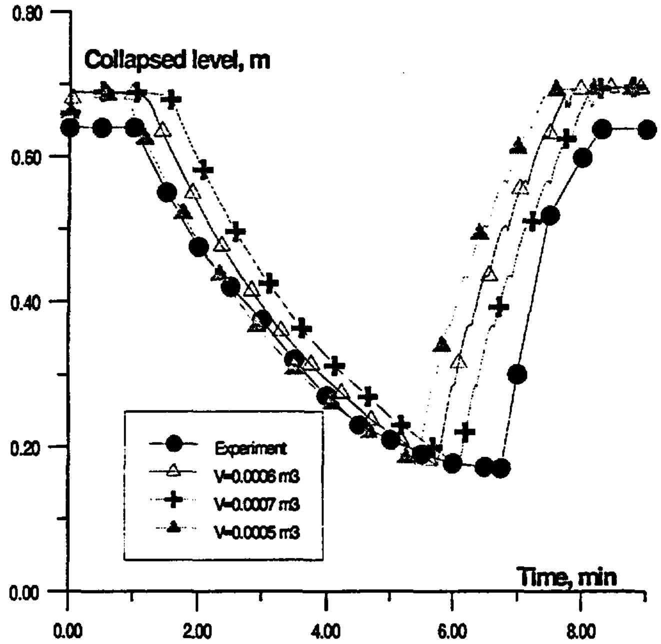

Fig. 22 Collapsed level behaviour with different upper volume

Another important parameter, which has a large influence on the results, is the power disturbance between pipe bundle and shroud. Fig.23 shows the results of calculations for distributions differed from base case – 80% for bundle and 20% for shroud.

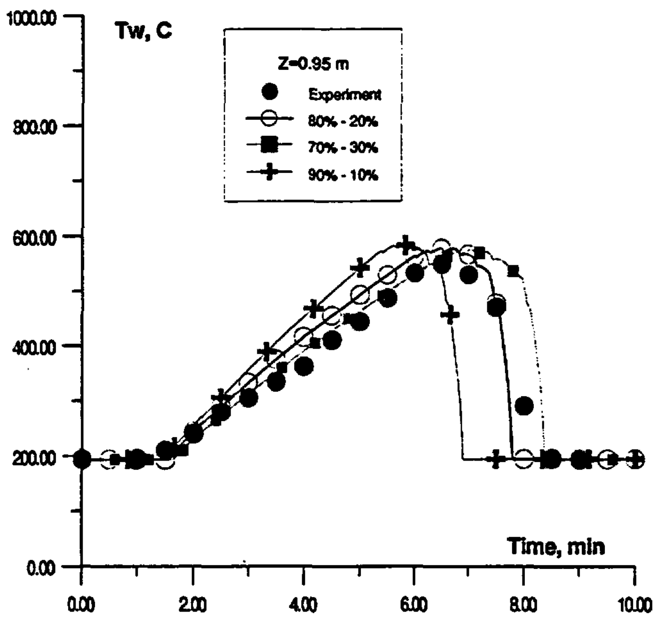

Fig. 23 Rod temperature behaviour at z=0.95m with different power distribution between rods and shroud

The influence of presence of six insulator rods is very small what is illustrated at Fig. 24.

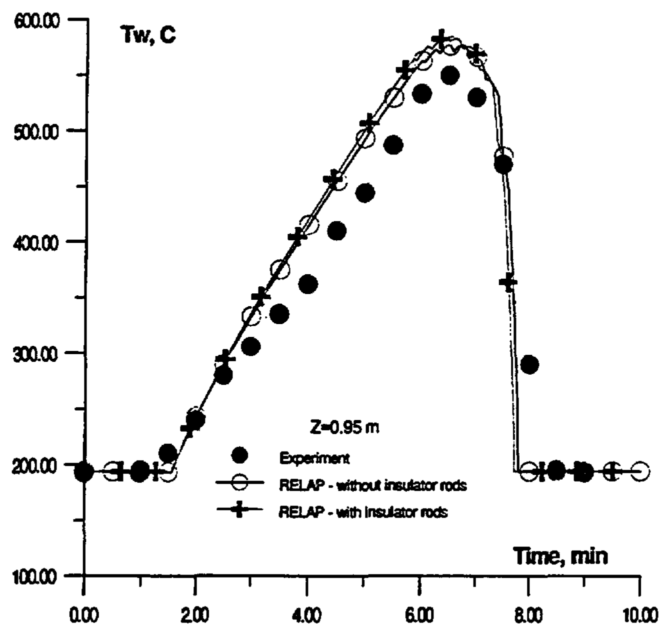

Fig. 24 Rod temperature behaviour at z=0.95m with taking into account presence of insulators

Besides that it was checked the influence of such parameters as temperature of water supplied into the upper plenum in the regimes without inlet flow and heat loss also. The calculations showed the influence of this value is very small also excluding the tests with very small inlet flowrates, when bundle power is the same order as the heat losses.

As for shroud temperature it was found the significant discrepancies between computed and measured values. Fig. 25-26 show the results of calculations and experimental ones for two locations of the test section. These calculations were made for two cases differed by power distribution between pipe bundle and shroud. The base case this distribution was 20% shroud power and the second – 30% shroud power. It is evident that this factor has small influence on the shroud temperature behaviour.

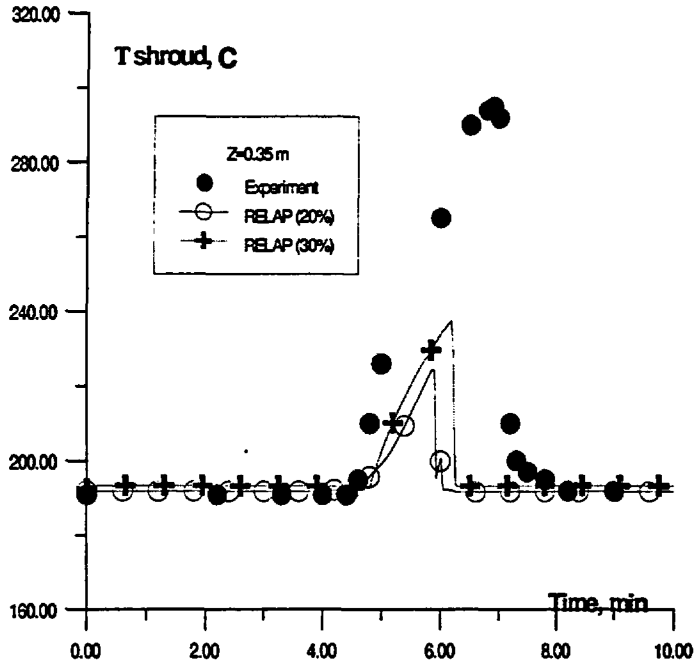

Fig. 25 Shroud temperature behaviour at z=0.35m

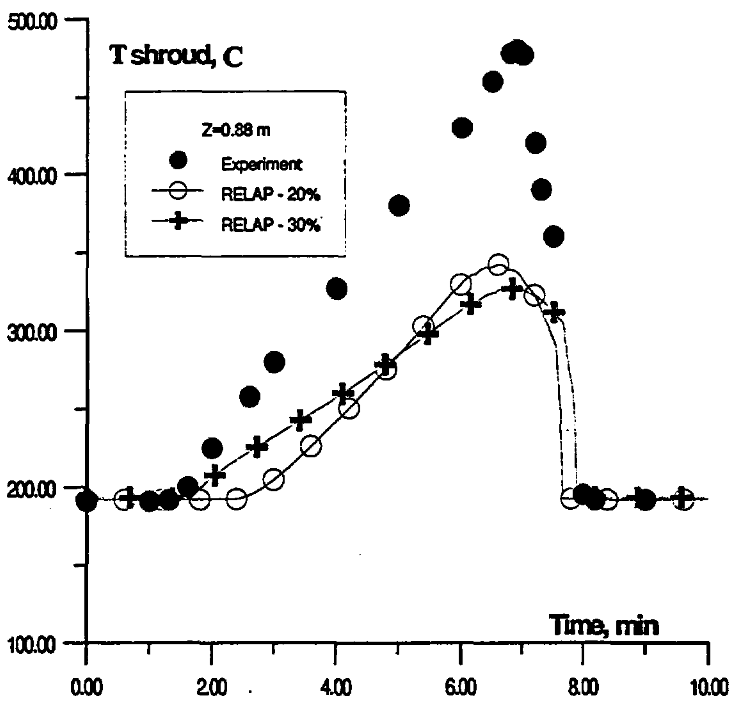

Fig. 26 Shroud temperature behaviour at z=0.88m

Another factor that could have an influence on the shroud temperature behavior is the heat losses value on its outer surface. Fig. 27-29 shows the results of calculations carried out with heat losses reduced by 20%. As one expect the shroud temperature becomes some larger, what illustrated by Fig. 27 for upper part of the shroud (Z=0.88m). For bottom part of the shroud the temperatures changed insignificantly and difference between experimental and computed temperature remains at former level (Fig. 29).

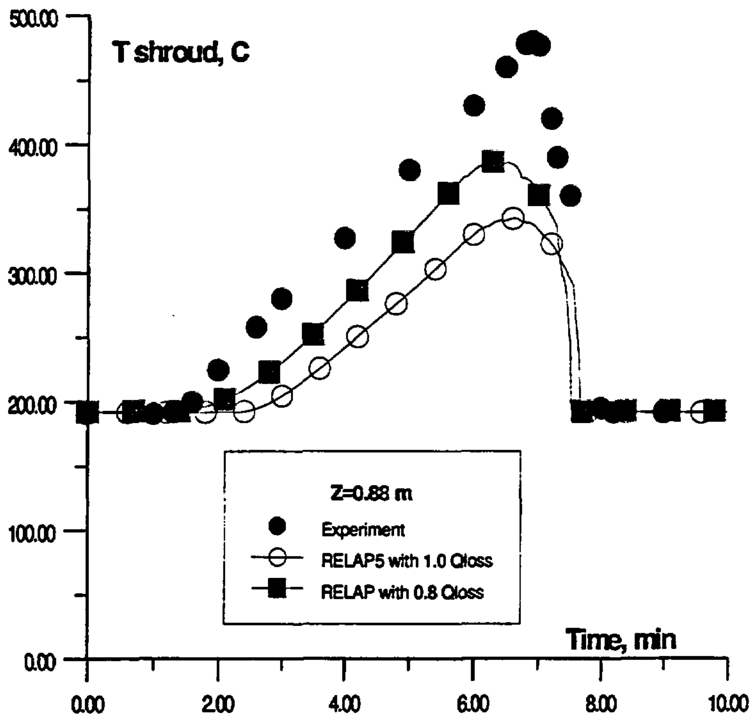

Fig. 27 Shroud temperature behaviour at z=0.88m with different heat losses

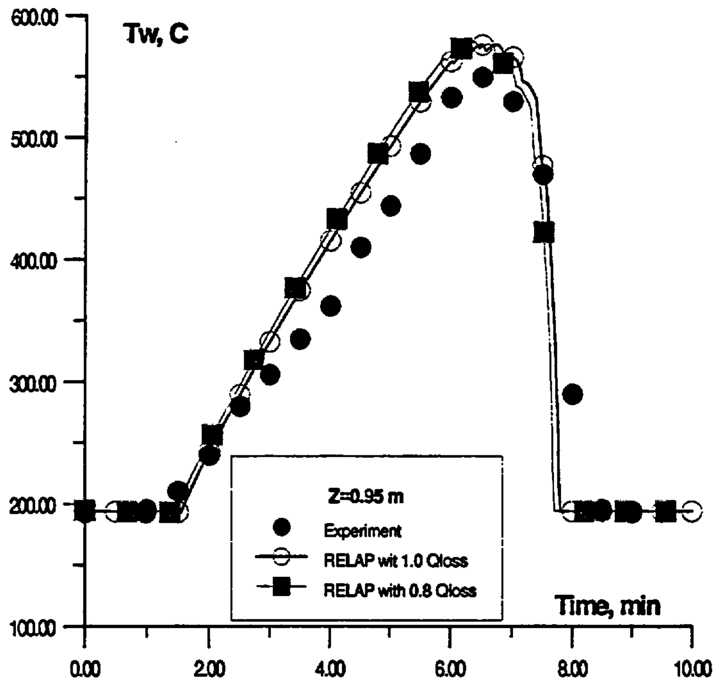

Fig. 28 Rod temperature behaviour at z=0.95m with different heat losses

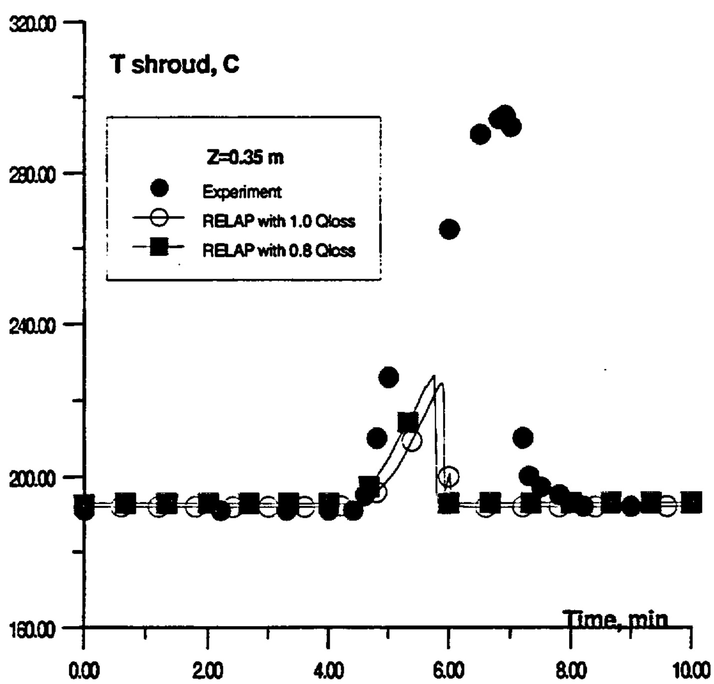

Fig. 29 Shroud temperature behaviour at z=0.35m with different heat losses

7. RUN STATISTICS

RELAP5/MOD3.2 code efficiency is illustrated by Fig. 30-31 where time step variation and CPU time during the calculation are presented. Grind time is evaluated as

CPU/(C*DT) = 0.00098 , where

C= 12 - volumes number,
DT = 8632 - time steps number,
CPU = 110 s - CPU time.

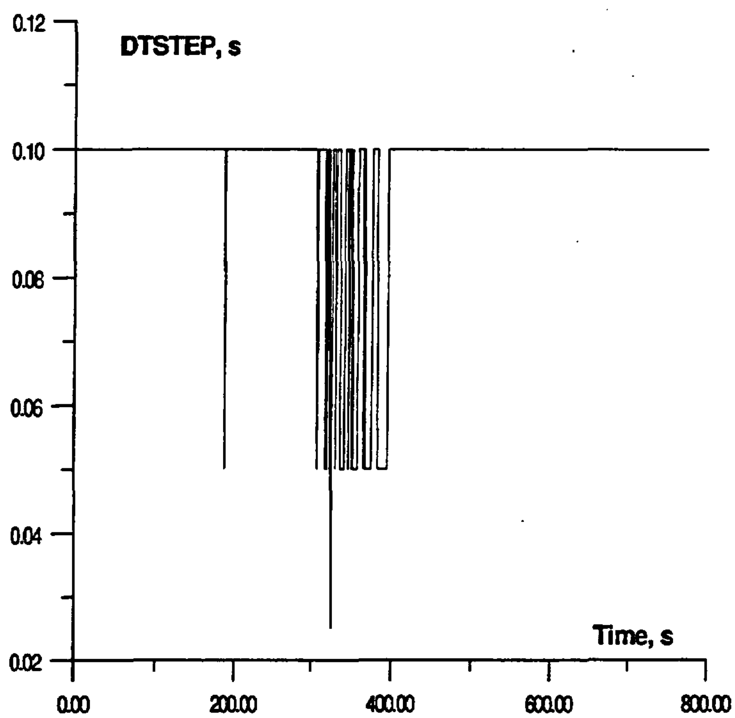

Fig. 30 Time step behaviour during boiloff and reflood test

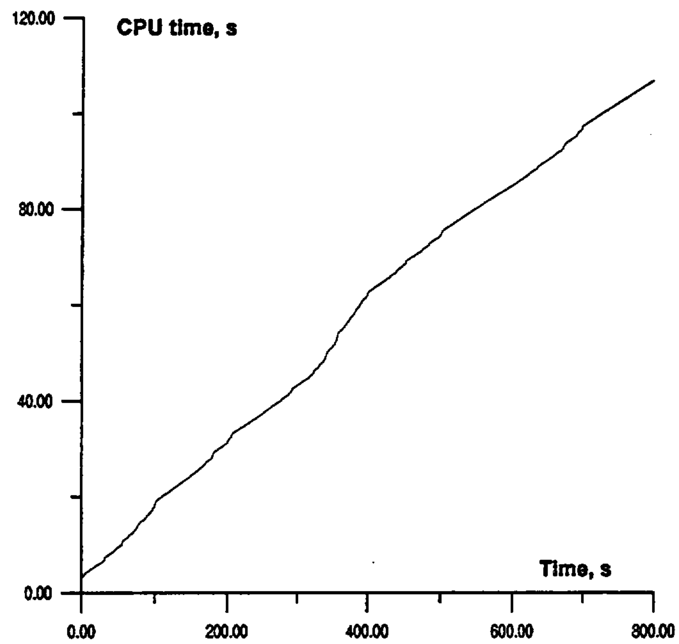

Fig. 31 CPU time during the test calculation

8. CONCLUSIONS

RELAP5/MOD3.2 assessment for processes proceeding in the rod bundle model with tight lattice was made. First series of the investigated experiments have been conducted at steady state conditions at small or zero flowrates at the inlet of the bundle. The comparison of computed with RELAP5/MOD3.2 results with experimental ones showed that for such processes code gives rather good results. The comparison of computed and experimental results for process of boil-off and reflooding shows that there is a good coordination between computed and experimental values between temperatures of pipe bundle walls for upper part of the bundle. For lower part of the bundle there are some discrepancies between computed and experimental values of temperature, the later being some lower than experimental ones. The calculated values of shroud temperature were rather less than experimental ones.

APPENDIX: RELAP5 INPUT DECK FOR BOILOFF AND REFLOOD TEST

```
=* CKTI boiloff test

0000100    new    transnt
*       time1   time2
0000105    5.0      10.0
0000110    air
*=======================================================================
*              time step control data
*=======================================================================
*        end time  min dt  max dt  optn    mnr    mjr   rst
0000202     100.0    1.0-9  0.10  00003   10     10000    100000
0000203     265.0    1.0-9  0.10  00003   10     10000    100000
0000204     300.0    1.0-9  0.10  00003   10     10000    100000
0000205     400.0    1.0-9  0.10  00003   10     10000    100000
0000206    800.0    1.0-9  0.10  00003   10     10000    100000
*=======================================================================
*------------------------------------------------------------
301       voidg  004070000
302       voidg  004090000
303       cntrlvar  02  * Gg1
304       cntrlvar  01  * Gg2
305       cntrlvar  04  *Wg01
306       cntrlvar  03  *Wg02
307       cntrlvar  05  *Hloss all
308       cntrlvar  06  *Hloss 1
309       cntrlvar  16  *Level
310       emass    0  *
311       mflowj  005000000  * outflow
312       tmass   0
313       dt      0
314       cntrlvar 14 *core mass
*
*--------------------------------------------------------------
*           max clad temperature greater than 820 K
0000501  cntrlvar  015   ge  null   0    820.0    1
*--------------------------------------------------------------
*
0020000      inleta  tmdpvol
*          ^^^^^^^^^^^^^^^^^^^
*          area   lengh    volume   azim. ang   ver ang   elev
0020101      0.0    10.0     10.0     0.0        0.0       0.0
*
*          rough    h. diam    fe
0020102      4.e-5    0.0       00
*
*          ebt
0020200      003
*
*          time    press    temp
0020201      0.0     1.32e6    464.46
```

```
0020202     500.0    1.32e6    464.46
*
*----------------------------------------------------------------
*----------------------------------------------------------------
*
0030000      inlet   tmdpjun
*        ^^^^^^^^^^^^^^^^^^^^
*     from       to          area
0030101   002000000   004000000     1.249e-3
*
0030200   1   501
*
*      h       liq flow     vap flow    int vel
0030201   0.0          00.0e-3    0.0       0.0
0030202   0.1          9.8e-3     0.0       0.0
0030203   1000.0       9.8e-3     0.0       0.0
*
*----------------------------------------------------------------
*================================================================================================
*                component 4
*                 core
*----------------------------------------------------------------
*
0040000       core   pipe
*         ^^^^^^^^^^^^^^^^^
0040001        10  * nvol
*
*          vol  area      vol no
0040101       1.249e-3       10
*          jun  area      jun no
0040201       1.072e-3       1  ** grid
0040202       1.249e-3       2
0040203       1.072e-3       3  ** grid
0040204       1.249e-3       4
0040205       1.072e-3       5  ** grid
0040206       1.249e-3       6
0040207       1.072e-3       7  ** grid
0040208       1.249e-3       8
0040209       1.072e-3       9  ** grid
*
*          vol length     vol
0040301       0.1          01
0040302       0.1          02
0040303       0.1          03
0040304       0.1          04
0040305       0.1          05
0040306       0.1          06
0040307       0.1          07  * void2
0040308       0.1          08
0040309       0.103          09  * void1
0040310       0.103          10  .
*
*          aver         vol no
0040601       90.0         10
*
*             rough         dhy        vol no
```

```
0040801     1.0-3       3.77e-3    10
*
*           floss       rloss    jun no
0040901      0.49        0.49       1
0040902      0.00        0.00       2
0040903      0.49        0.49       3
0040904      0.00        0.00       4
0040905      0.49        0.49       5
0040906      0.00        0.00       6
0040907      0.49        0.49       7
0040908      0.00        0.00       8
0040909      0.49        0.49       9

*           pvbfe         vol no
0041001      01000          10
0041001      01100          10  * bundle
*           fvcahs        jun no
0041101      001000         9
*
*           ebt        p            t                vol no
0041201      003    1.32533e6    465.645  0.0  0.0  0.0   1
0041202      003    1.32466e6    465.622  0.0  0.0  0.0   2
0041203      003    1.32404e6    465.601  0.0  0.0  0.0   3
0041204      003    1.32343e6    465.579  0.0  0.0  0.0   4
0041205      003    1.32285e6    465.560  0.0  0.0  0.0   5
0041206      003    1.32229e6    465.540  0.0  0.0  0.0   6
0041207      003    1.32176e6    465.522  0.0  0.0  0.0   7
0041208      003    1.32124e6    465.504  0.0  0.0  0.0   8
0041209      003    1.32075e6    465.487  0.0  0.0  0.0   9
0041210      003    1.32025e6    465.470  0.0  0.0  0.0   10
*
0041300      0  *  ctrl word
*
*           flowf     flowg      win  jun no
0041301      0.0       0.0       0.0   9
*=================================================================================
*-----------------------------------------------------
0050000  uppl   sngljun
*          from          to         area     floss   rloss   fvcahs
0050101  004010000  006000000  1.072e-3  0.5     0.5    001000
0050101  004010000  008000000  1.072e-3  0.5     0.5    001000
*        flowf  flowg       win
0050201  1  0.0      0.0       0.0
*
*---- ----1---- ----2---- ----3---- ----4---- ----5---- ----6---- ----7
*0060000  up   snglvol
*0060101  6.32e-4    0.065  0.0000    0.0     90.0     0.065
**                 pvbfe
*0060102  4.0-5    0.0      01000
*0060200  003  1.32+6  465.2   0.0      0.0     0.0
**================================================================================
====
**-----------------------------------------------------
*0070000  uppl   sngljun
**
**        from       to         area      floss    rloss  fvcahs
```

```
*0070101  006010000  008000000  2515.e-6  0.155   0.155  101000
**          flowf  flowg        win
*0070201  1  00.0e-3   0.0      0.0
**
**---- ----1---- ----2---- ----3---- ----4---- ----5---- ----6---- ----7
0080000  up   snglvol
0080101  20.0e-4    0.165 0.0     0.6e-4     90.0     0.165
*                        pvbfe
0080102  4.0-5    0.0     01000
0080200  003  1.32+6   465.2    0.0      0.0     0.0
*=========================================================================*-----------
-------------------------------------------
0090000  uppl   sngljun
*      D = 18 mm
*          from            to         area     floss  rloss  fvcahs
0090101  008010000  010000000  254.34e-6   2.0  2.0  000000*
*            flowf  flowg        win
0090201  1  00.0e-3   0.0       0.0
*
*------------------------------------------------------------
*
0100000      outlet  tmdpvol
*       ^^^^^^^^^^^^^^^^^^^^^^
*          area   lengh    volume   azim. ang   ver ang   elev
0100101      0.0    10.0     10.0    0.0         0.0      0.0
*
*          rough     h. diam
0100102      4.e-5    0.0      00000
*
*          ebt
0100200      002
*
*          time    press    temp
0100201      0.0     1.32e6      1.00
0100202    500.0     1.32e6      1.00
*------------------------------------------------------------
*
*             HEAT  STRUCTURES
*
*=========================================================================*
bundle
*-----------------------------------
*          nh    np    geom    st-st   left
10101000    10    4     2       0    2.0e-3
*
10101100    0   1
*
10101101    3    3.0e-3
*
10101201    004   3
*
10101301    1.0  3

10101401    467.5   4
*
*
```

```
10101501  0     0   0   1   5.5  1  *(0.1*55tubes=5.5)
10101502  0     0   0   1   5.5  2
10101503  0     0   0   1   5.5  3
10101504  0     0   0   1   5.5  4
10101505  0     0   0   1   5.5  5
10101506  0     0   0   1   5.5  6
10101507  0     0   0   1   5.5  7
10101508  0     0   0   1   5.5  8
10101509  0     0   0   1   5.655  9
10101510  0     0   0   1   5.655  10 *(0.103*55=5.655)
*
10101601  004010000 0   1    1  5.5    1
10101602  004020000 0   1    1  5.5    2
10101603  004030000 0   1    1  5.5    3
10101604  004040000 0   1    1  5.5    4
10101605  004050000 0   1    1  5.5    5
10101606  004060000 0   1    1  5.5    6
10101607  004070000 0   1    1  5.5    7
10101608  004080000 0   1    1  5.5    8
10101609  004090000 0   1    1  5.655    9
10101610  004100000 0   1    1  5.655    10
* *
10101701  100     0.1     0     0     10  *
*
*         left    chf    lhf  lhb    gslf gslr glcf  gcr  bf   no
10101801  0.0     10.0   10.0   0.0  0.0  0.0  0.0  1.0  10
*
10101901  6.0e-3  10.0   10.0   0.0  0.0  0.0  0.0  1.0   10
*-----------------------------------------------------------
*         shroud
*-------------------------------------
*          nh    np   geom   st-st  left
10201000   10    4    2       0   30.5e-3
*
10201100   0  1
*
10201101   3  31.5e-3
*
10201201   004  3
*
10201301   1.0  3
*
10201401   465.5  4
*
*
10201501  004010000 0   1    1    0.1  1
10201502  004020000 0   1    1    0.1  2
10201503  004030000 0   1    1    0.1  3
10201504  004040000 0   1    1    0.1  4
10201505  004050000 0   1    1    0.1  5
10201506  004060000 0   1    1    0.1  6
10201507  004070000 0   1    1    0.1  7
10201508  004080000 0   1    1    0.1  8
10201509  004090000 0   1    1    0.103 9
10201510  004100000 0   1    1    0.103 10
*
```

```
10201601   -700    0   3701   1   0.1  1
10201602   -700    0   3701   1   0.1  2
10201603   -700    0   3701   1   0.1  3
10201604   -700    0   3701   1   0.1  4
10201605   -700    0   3701   1   0.1  5
10201606   -700    0   3701   1   0.1  6
10201607   -700    0   3701   1   0.1  7
10201608   -700    0   3701   1   0.1  8
10201609   -700    0   3701   1   0.103 9
10201610   -700    0   3701   1   0.103 10
**
10201701   101     0.1     0     0     10  *
*
*          left   chf    lhf  lhb   gslf gslr glcf  gcr bf   no
10201801   0      10.0   10.0   0.0  0.0  0.0  0.0 1.0  10
*
10201901   0.0    10.0   10.0   0.0  0.0  0.0  0.0 1.0   10
*
*
*=====================================================================
*        heat structure thermal property data
*=====================================================================
*
*        mtl.type    th.con    ht.cap
20100400  tbl/fctn     1        1 * tube.(gamma=7.9 g/cm*cm*cm)
*
*=====================================================================
*           thermal conductivity tube
*=====================================================================
*
*crdno     temp        th.con.
20100401  273.15       15.3
20100402  373.15       16.9
20100403  473.15       18.1
20100404  573.15       19.5
20100405  673.15       20.3
20100406  800.15       21.6
20100407  900.15       23.3
20100408  1000.15       25.0
*
*=====================================================================
*          volumetric heat capacity tube
*=====================================================================
*
*crdno     temp        ht.cap.
20100451  273.15       3.803+6
20100452  373.15       3.903+6
20100453  473.15       4.063+6
20100454  573.15       4.234+6
20100455  673.15       4.329+6
20100456  800.15       4.329+6
20100457  900.15       4.329+6
20100458  1000.15       4.210+6
*
*=====================================================================
*                  general tables
```

```
*=============================================================================
*
* power table
*        Q total=9.3 kW  for test 3D (0.8)
*crdno    name    trip
20210000  power   501
*
*crdno     time     power Wt
*
20210001   0.0     0.744e4
20210002   0.1     0.744e4
*------------------------------------------------
*
* power table    shroud (20%)
*
*crdno    name    trip
20210100  power   501
*
*crdno     time     power wt
*
20210101   0.0     0.1860e4
20210102   5.0     0.1860e4
*------------------------------------------------
*
* power table   preheater
*
*crdno    name    trip
20210200  power   501
*
*crdno     time     power wt
*
20210201    0.0      7.55e3
20210202    1.0      7.55e3  *
20210203   10.0      7.55e3
20210204  500.0      7.55e3
*------------------------------------------------
*
*        temperature in containment
*        ^^^^^^^^^^^^^^^^^^^^^^^^^^^
20270000      temp
*
20270002      0.0   300.0
20270003      1.0    300.0
20270004      1.0e6   300.0
*------------------------------------------------------------------
20270100      htc-t   0   1.0   1.0
*   Q core= 13.5*(t-20)=13.5*(465.5-300)=2234
20270101      -1.0     64.381   * core
20270102       0.0     64.381   * h=Q/dt/(3.14*D*L)
20270102       0.0     64.381   * h=13.5/3.14/63e-3/1.06=64.381
20270103       1.0     64.381.
20270104    10000.0     64.381
*
*------------------------------------------------------------------
20270200      htc-t   0   1.0   1.0 *preheater
*
```

```
20270201      -1.0      50.55   * h=Q/(3.14 D L)= 5/3.14/63e-3/0.5
20270202       0.0      50.55
20270203     100.0      50.55
*
*------------------------------------------------------------

*
20500100  GG2  mult   1.249e-3   0.0  0
20500101  rhogj    004070000
20500102  velgj    004070000
20500103  voidgj    004070000
*
20500200  GG1  mult   1.249e-3   0.0  0
20500201  rhogj    004090000
20500202  velgj    004090000
20500203  voidgj    004090000
*
20500300  W0G1  mult   1.0      0.0  0
20500301  velgj    004090000
20500302  voidgj    004090000
*
20500400  W0G2  mult   1.0      0.0  0
20500401  velgj    004070000
20500402  voidgj    004070000
*
20500500   "Hloss"     sum   -0.19782e-3    0  1
20500501          0.0    0.1     htrnr   020100101
20500502                 0.1     htrnr   020100201
20500503                 0.1     htrnr   020100301
20500504                 0.1     htrnr   020100401
20500505                 0.1     htrnr   020100501
20500506                 0.1     htrnr   020100601
20500507                 0.1     htrnr   020100701
20500508                 0.1     htrnr   020100801
20500509                 0.103   htrnr   020100901
20500510                 0.103   htrnr   020101001
*     S = 3.14*D*dz= 3.14*63/1000*dz=0.19782 *dz m2
*
*
20500600   "Qbun"     sum     0.01884     0  1
20500601          0.0    5.5     htrnr   020100101
20500602                 5.5     htrnr   020100201
20500603                 5.5     htrnr   020100301
20500604                 5.5     htrnr   020100401
20500605                 5.5     htrnr   020100501
20500606                 5.5     htrnr   020100601
20500607                 5.5     htrnr   020100701
20500608                 5.5     htrnr   020100801
20500609                 5.655   htrnr   020100901
20500610                 5.655   htrnr   020101001
*     S = 3.14*d*dz= 3.14*6e-3*dz=0.01884 *dz m2
*
20500700   "Qshr"     sum     0.19782     0  1
20500701          0.0    0.1     htrnr   020100100
20500702                 0.1     htrnr   020100200
20500703                 0.1     htrnr   020100300
```

```
20500704            0.1    htrnr  020100400
20500705            0.1    htrnr  020100500
20500706            0.1    htrnr  020100600
20500707            0.1    htrnr  020100700
20500708            0.1    htrnr  020100800
20500709            0.103   htrnr  020100900
20500710            0.103   htrnr  020101000
*     S = 3.14*D*dz= 3.14*63/1000*dz=0.19782 *dz m2
*--------------------------------------------
*
20500800 q     sum    0.769  0.      1
20500801 0.0     1.0    cntrlvar   06   * Qrods+Qshroud
20500802         1.0    cntrlvar   07
*
*  q = Q(Ph*L)= (cntrlvar 8)/[3.148(61e-3+6e-3*55)*1.06] =
*     = (cntrlvar 8)/1.3= 0.769*(cntrlvar 8)
*----------------------------------------------------
*   Ph= 3.14*(61e-3+6e-3*55) =1.227
*   dMl/dt= -q*Ph*L/r
*----------------------------------------------
*
*     name    type    scale   init     flag
20500900 r      sum     1.0    0.      1
20500901 0.0     1.0    sathg      004010000
20500902        -1.0    sathf     004010000
*
*
*------------------------------
*        Ph*L/r
*        Ph*L= 1.277*1.06=1.3
*
20501000  "Ph*L/r" div   1.3    0.0     1
20501001  cntrlvar  09
*
*
*                        init value
20501100  "Int"  integral -1.0    0.0      1
20501101  cntrlvar  08
*
*
*
20501200  "Mlout"  mult     1.0    0.0   1
20501201  cntrlvar  10  cntrlvar  11
*
*
*     name   type    scale   init     flag
20501300  "Mliq"     sum     1.0     0.76    1
20501301  0.76    1.0    cntrlvar   12
*
*----------------------------------------
*        Mass=rho*Lev*s
*     name   type    scale   init     flag
20501400  "Mcore"    mult   1.249e-3  0.0    1
20501401  rhof 004010000  cntrlvar   16
*
*
```

```
*
*       max clad temperature
20501500  maxtemp  stdfnctn   1.0   0.0    1
*       ^^^^^^^^^^^^^^^^^
20501501   max   httemp      010100104
20501502         httemp     010100204
20501503         httemp     010100304
20501504         httemp     010100404
20501505         httemp     010100504
20501506         httemp     010100604
20501507         httemp     010100704
20501508         httemp     010100804
20501509         httemp     010100904
20501510         httemp     010101004
*
*
*
20501600    corelev  sum   1.0   0.0   1
*         ^^^^^^^^^^^
20501601    0.0    0.1   voidf    004010000
20501602           0.1   voidf    004020000
20501603           0.1   voidf    004030000
20501604           0.1   voidf    004040000
20501605           0.1   voidf    004050000
20501606           0.1   voidf    004060000
20501607           0.1   voidf    004070000
20501608           0.1   voidf    004080000
20501609           0.103  voidf    004090000
20501610           0.103  voidf    004100000
*------------------------------------------------------------------
*
20501700    vesslev  sum   1.0   0.0   1
*         ^^^^^^^^^^^
20501701·   0.0    0.1   voidf    004010000
20501702           0.1   voidf    004020000
20501703           0.1   voidf    004030000
20501704           0.1   voidf    004040000
20501705           0.1   voidf    004050000
20501706           0.1   voidf    004060000
20501707           0.1   voidf    004070000
20501708           0.1   voidf    004080000
20501709           0.103  voidf    004090000
20501710           0.103  voidf    004100000
20501711           0.1586 voidf    008010000
*------------------------------------------------------------------
*
20502000  Gdown  mult   1.072e-3   0.0  0
20502001  rhofj    005000000
20502002  velfj    005000000
20502003  voidfj    005000000
*
*
20502100  "liqdown"  integral  1.0     0.0      1
20502101  cntrlvar   20
*
*
```

```
20502200  Gvout  mult  254.34e-6  0.0 0
20502201  rhogj     009000000
20502202  velgj     009000000
20502203  voidgj    009000000
*
*
20502300  "Gvout"  integral  1.0     0.0     1
20502301  cntrlvar   22
*
*      name    type    scale   init    flag
20501900 "Mass"    sum     1.0    0.      1
20501901  0.0      1.0    tmass     0
20501902          -1.0    cntrlvar   23
*
*
```

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report presents the results of RELAP5/MOD3.2 assessment in the prediction of two-phase hydrodynamics and heat transfer in rod bundle model with tight lattice. The experiments have been carried out at the CKTI (St. Petersburg) test facility. The peculiarities of these researches were the non-standard geometrical characteristics of the 55-rod bundle - close packed assembly and small hydraulic diameters, and also the parameters - small flow rates (down to zero) and low pressure (from 0.23 up to 2.0 MPa). The assessment of RELAP5/MOD3.2 code was done for two cases: for steady state conditions at small or zero flowrates at the inlet of the rod bundle and for boil-off and reflooding processes. The comparison of calculated results with experimental ones shows that there was a good coordination between computed and experimental values of void fractions and bundle wall temperatures for almost all the tests.

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