

Министерство науки и высшего образования Российской Федерации
 федеральное государственное автономное
 образовательное учреждение высшего образования
 «Национальный исследовательский Томский политехнический университет» (ТПУ)

Инженерная школа ядерных технологий
Направление подготовки 14.04.02 Ядерные физика и технологии
Отделение ядерно-топливного цикла

МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

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| Тема работы |
| Теплогидравлический расчёт ТВС ИРТ-3М в реакторе ИРТ-Т с различными поверхностями теплообмена |

УДК 621.039.55:621.039.517

Студент

| Группа | ФИО | Подпись | Дата |
|--------|---------------------------|---------|------|
| 0АМ8И | Немыкин Никита Валерьевич | | |

Руководитель ВКР

| Должность | ФИО | Ученая степень, звание | Подпись | Дата |
|---------------------|------------|------------------------|---------|------|
| Профессор ОЯТЦ ИЯТШ | Бутов В.Г. | д.ф-м.н. | | |

КОНСУЛЬТАНТЫ ПО РАЗДЕЛАМ:

По разделу «Финансовый менеджмент, ресурсоэффективность и ресурсосбережение»

| Должность | ФИО | Ученая степень, звание | Подпись | Дата |
|-----------------|-----------------|------------------------|---------|------|
| Доцент ОСГН ШИП | Меньшикова Е.В. | к.ф.н. | | |

По разделу «Социальная ответственность»

| Должность | ФИО | Ученая степень, звание | Подпись | Дата |
|------------------|--------------|------------------------|---------|------|
| Доцент ОЯТЦ ИЯТШ | Веригин Д.А. | к.ф-м.н | | |

ДОПУСТИТЬ К ЗАЩИТЕ:

| Руководитель ООП | ФИО | Ученая степень, звание | Подпись | Дата |
|--|------------------|------------------------|---------|------|
| Nuclear Power Installation Operation (Управление ядерной энергетической установкой) | Верхотурова В.В. | к.и.н. | | |

Министерство науки и высшего образования Российской Федерации
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School of Nuclear Science and Engineering

Field of training (specialty) 14.04.02 Nuclear Science and Technology, Nuclear Power Installation Operation

Nuclear Fuel Cycle Division

MASTER THESIS

| |
|--|
| Topic of research work |
| Thermal-hydraulic calculation of IRT-3M type fuel assembly in the IRT-T reactor with various energy conduction surfaces |

UDC 621.039.55:621.039.517

Student

| Group | Full name | Signature | Date |
|-------|------------------------------|-----------|------|
| 0AM8И | Nemykin Nikita Valerevich | | |

Scientific supervisor

| Position | Full name | Academic degree, academic rank | Signature | Date |
|-----------|------------|-----------------------------------|-----------|------|
| Professor | V.G. Butov | PhD | | |

ADVISERS:

Section “Financial Management, Resource Efficiency and Resource Saving”

| Position | Full name | Academic degree, academic rank | Signature | Date |
|------------------------|----------------------------|-----------------------------------|-----------|------|
| Associate Professor | Ekaterina V. Menshikova | PhD | | |

Section “Social Responsibility”

| Position | Full name | Academic degree, academic rank | Signature | Date |
|------------------------|----------------|-----------------------------------|-----------|------|
| Associate Professor | Dan A. Verigin | PhD | | |

ADMITTED TO DEFENSE:

| Programme Director | Full name | Academic degree, academic rank | Signature | Date |
|--|-------------------------|-----------------------------------|-----------|------|
| Nuclear Power Installation Operation | Vera V. Verkhoturova | PhD | | |

Tomsk – 2019

Министерство науки и высшего образования Российской Федерации
 федеральное государственное автономное
 образовательное учреждение высшего образования
 «Национальный исследовательский Томский политехнический университет» (ТПУ)

School of Nuclear Science and Engineering
Field of training (specialty) 14.04.02 Nuclear Science and Technology, Nuclear Power Installation
Operation
Nuclear Fuel Cycle Division

APPROVED BY:
 Programme Director
 _____ Verkhoturova V.V.
 « ____ » _____ 2020

**ASSIGNMENT
for the Graduation Thesis completion**

In the form:

| |
|---------------|
| Master Thesis |
|---------------|

For a student:

| Group | Full name |
|-------|---------------------------|
| 0AM8I | Nemykin Nikita Valerevich |

Topic of research work:

| | |
|--|-----------------------|
| | |
| Approved by the order of the Director of School of Nuclear Science & Engineering (date, number): | №129-/c at 08.05.2020 |

| | |
|---|------------|
| Deadline for completion of Master Thesis: | 01.06.2020 |
|---|------------|

TERMS OF REFERENCE:

| | |
|---|--|
| Initial date for research work: <i>(the name of the object of research or design; performance or load; mode of operation (continuous, periodic, cyclic, etc.); type of raw material or material of the product; requirements for the product, product or process; special requirements to the features of the operation of the object or product in terms of operational safety, environmental impact, energy costs; economic analysis, etc.)</i> | – Ansys-CFX software; – Inlet parameters of the coolant; – Geometrical parameters of fuel assemblies |
|---|--|

| | |
|---|---|
| <p>List of the issues to be investigated, designed and developed <i>(analytical review of literary sources with the purpose to study global scientific and technological achievements in the target field, formulation of the research purpose, design, construction, determination of the procedure for research, design, and construction, discussion of the research work results, formulation of additional sections to be developed; conclusions).</i></p> | <ul style="list-style-type: none"> - Thermal-hydraulic performance of the IRT-3M type fuel assembly during its exploitation in the reactors core; - Design of the geometrical model of fuel assembly with various heat-conducting surfaces; - Simulation of the performance of fuel assembly in reactor's core |
|---|---|

| | |
|---|--|
| <p>List of graphic material <i>(with an exact indication of mandatory drawings)</i></p> | |
|---|--|

Advisors to the sections of the Master Thesis
(with indication of sections)

| Section | Advisor |
|--|-----------------|
| One: Literature review | V.G. Butov |
| Two: Experimental part | V.G. Butov |
| Three: Financial Management, resource efficiency and resource saving | E.V. Menshikova |
| Four: Social responsibility | D.A. Verigin |

| | |
|---|--|
| <p>Date of issuance of the assignment for Master Thesis completion according to the schedule</p> | |
|---|--|

Assignment issued by a scientific supervisor / advisor (if any):

| Position | Full name | Academic degree, academic status | Signature | Date |
|-----------|------------|----------------------------------|-----------|------|
| Professor | V.G. Butov | PhD | | |

Assignment accepted for execution by a student:

| Group | Full name | Signature | Date |
|-------|---------------------------|-----------|------|
| 0AM8I | Nemykin Nikita Valerevich | | |

**TASK FOR SECTION
«FINANCIAL MANAGEMENT, RESOURCE EFFICIENCY AND RESOURCE SAVING»**

To the student:

| | |
|--------------|------------------|
| Group | Full name |
| 0AM8И | N.V. Nemykin |

| | | | |
|---------------|-------------------------------|----------------------------|--------------------------------------|
| School | Nuclear science & Engineering | Division | Nuclear-Fuel cycle |
| Degree | Master | Educational Program | Nuclear Power Installation Operation |

Input data to the section «Financial management, resource efficiency and resource saving»:

| | |
|--|--|
| 1. <i>Resource cost of scientific and technical research (STR): material and technical, energetic, financial and human</i> | – Salary costs – 143775; – STR budget – 213954; |
| 2. <i>Expenditure rates and expenditure standards for resources</i> | – Electricity costs – 5,8 rub per 1 kW |
| 3. <i>Current tax system, tax rates, charges rates, discounting rates and interest rates</i> | – Labor tax – 27,1 %; – Overhead costs – 30%; |

The list of subjects to study, design and develop:

| | |
|---|--|
| 1. <i>Assessment of commercial and innovative potential of STR</i> | – comparative analysis with other researches in this field; |
| 2. <i>Development of charter for scientific-research project</i> | – SWOT-analysis; |
| 3. <i>Scheduling of STR management process: structure and timeline, budget, risk management</i> | – calculation of working hours for project; – creation of the time schedule of the project; – calculation of scientific and technical research budget; |
| 4. <i>Resource efficiency</i> | – integral indicator of resource efficiency for the developed project. |

A list of graphic material (with list of mandatory blueprints):

1. *Competitiveness analysis*
2. *SWOT- analysis*
3. *Gantt chart and budget of scientific research*
4. *Assessment of resource, financial and economic efficiency of STR*
5. *Potential risks*

| | |
|--|------------|
| Date of issue of the task for the section according to the schedule | 05.03.2020 |
|--|------------|

Task issued by adviser:

| | | | | |
|---------------------|------------------|--------------------------------|------------------|-------------|
| Position | Full name | Scientific degree, rank | Signature | Date |
| Associate professor | E.V. Menshikova | PhD | | |

The task was accepted by the student:

| | | | |
|--------------|------------------|------------------|-------------|
| Group | Full name | Signature | Date |
| 0AM8И | N.V. Nemykin | | |

Task for section «Social responsibility»

To student:

| group | Full name |
|-------|---------------------------|
| 0AM8I | Nemykin Nikita Valerevich |

| | | | |
|--------|---------------------------------|----------------|--------------------------------------|
| School | Nuclear Science and Engineering | Department | Nuclear fuel cycle |
| Degree | Master programme | Specialization | Nuclear Power Installation Operation |

Title of graduation thesis:

| | |
|---|---|
| Thermal-hydraulic calculation of IRT-3M type fuel assembly in the IRT-T reactor with various energy conduction surfaces | |
| Initial data for section «Social Responsibility»: | |
| 1. Information about object of investigation (matter, material, device, algorithm, procedure, workplace) and area of its application | IRT-3M fuel assembly. Application area: nuclear reactor |
| List of items to be investigated and to be developed: | |
| 1. Legal and organizational issues to provide safety: <ul style="list-style-type: none"> – Special (specific for operation of objects of investigation, designed workplace) legal rules of labor legislation; – Organizational activities for layout of workplace. | <ul style="list-style-type: none"> – Labour code of Russian Federation #197 from 30/12/2001 GOST 12.2.032-78 SSBT – Sanitary Rules 2.2.2/2.4.1340-03. Hygienic requirements for PC and work with it |
| 2. Work Safety: 2.1. Analysis of identified harmful and dangerous factors 2.2. Justification of measures to reduce probability of harmful and dangerous factors | <ul style="list-style-type: none"> – Enhanced electromagnetic radiation level – Insufficient illumination of workplace – Excessive noise – Deviation of microclimate indicators – Electric shock |
| 3. Ecological safety: | <ul style="list-style-type: none"> – Indicate impact of nuclear power plant on hydrosphere, atmosphere and lithosphere |
| 4. Safety in emergency situations: | <ul style="list-style-type: none"> – Fire safety; |

| | |
|---|----------|
| Assignment date for section according to schedule | 03.04.20 |
|---|----------|

The task was issued by consultant:

| Position | Full name | Scientific degree, rank | Signature | date |
|---------------------|--------------|-------------------------|-----------|------|
| Assistant professor | Verigin D.A. | Cand.of Sc. | | |

The task was accepted by the student:

| Group | Full name | Signature | date |
|-------|---------------------------|-----------|------|
| 0AM8I | Nemykin Nikita Valerevich | | |

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School of Nuclear Science and Engineering

Field of training (specialty) 14.04.02 Nuclear Science and Technology, Nuclear Power Installation Operation

Level of education: Master degree programme

Nuclear Fuel Cycle Division

Period of completion: spring semester 2019/2020 academic year

Form of presenting the work:

Master Thesis

**SCHEDULED ASSESSMENT CALENDAR
for the Master Thesis completion**

| | |
|--|------------|
| Deadline for completion of Master's Graduation Thesis: | 01.06.2020 |
|--|------------|

| Assessment date | Title of section (module) / type of work (research) | Maximum score for the section (module) |
|-----------------|---|--|
| 03.04.2020 | <i>Obtaining the assignment</i> | |
| 08.04.2020 | <i>Familiarization with ANSYS CFX package</i> | |
| 13.04.2020 | Development of a geometrical models of fuel assemblies | |
| 18.04.2020 | <i>Development computational models of fuel assemblies in ANSYS CFX</i> | |
| 25.04.2020 | <i>Report writing</i> | |

COMPILED BY:

Scientific supervisor:

| Position | Full name | Academic degree, academic status | Signature | Date |
|----------|-----------|----------------------------------|-----------|------|
| | | | | |

AGREED BY:

| Programme Director | Full name | Academic degree, academic status | Signature | Date |
|--------------------------------------|----------------------|----------------------------------|-----------|------|
| Nuclear Power Installation Operation | Vera V. Verkhoturova | PhD | | |

Expected learning outcomes

| Learning outcome (LO) code | Learning outcome (a graduate should be ready) | Requirements of the FSES HE, criteria and / or interested parties |
|--|--|--|
| <i>Professional competencies</i> | | |
| LO1 | To apply deep mathematical, scientific, socio-economic and professional knowledge for conducting theoretical and experimental research in the field of the use of nuclear science and technology. | FSES HE Requirements (PC-1,2, 3, 6, UC-1,3), Criterion 5 RAEE (p 1.1) |
| LO2 | To demonstrate ability to define, formulate, and solve interdisciplinary engineering tasks in the nuclear field using professional knowledge and modern research methods. | FSES HE Requirements (PC-2,6,9,10,14, UC-2,3,4, BPC1,2), Criterion 5 RAEE (p 1.2) |
| LO3 | To plan and conduct analytical, simulation and experimental studies in complex and uncertain conditions using modern technologies, and to evaluate critically research results. | FSES HE Requirements (PC-4,5,6,9,22, UC-1,2,5,6), Criterion 5 RAEE (p 1.3) |
| LO4 | To use basic and special approaches, skills and methods for identification, analysis, and solution of technical problems in the field of nuclear science and technology. | FSES HE Requirements (PC-7,10,11,12,13, UC-1-3,BPC1,3), Criterion 5 RAEE (p 1.4) |
| LO5 | To operate modern physical equipment and instruments, to master technological processes in the course of preparation for the production of new materials, instruments, installations, and systems. | FSES HE Requirements (PC-8,11,14,15, BPC-1), Criterion 5 RAEE (p 1.3) |
| LO6 | To demonstrate ability to develop multioption schemes for achieving production goals with the effective use of available technical means and resources. | FSES HE Requirements (PC-12,13,14,16, BPC-2), Criterion 5 RAEE (p 1.3) |
| <i>Cultural competencies</i> | | |
| LO7 | To demonstrate ability to use a creative approach to develop new ideas and methods for designing nuclear facilities, as well as to modernize and improve the applied technologies of nuclear production. | FSES HE Requirements (PC-2,6,9,10,14, UC-1,2,3), Criterion 5 RAEE (p 1.2,2.4,2.5) |
| <i>Basic professional competencies</i> | | |
| LO8 | To demonstrate skills of independent learning and readiness for continuous self-development within the whole period of professional activity. | FSES HE Requirements (PC-16,17,21, UC-5,6, BPC-1), Criterion 5 RAEE (p 2.6) coordinated with the requirements of the international standard EURACE & FEANI |

| | | |
|------|---|---|
| LO9 | To use a foreign language at a level that enables a graduate to function successfully in the international environment, to develop documentation, and to introduce the results of their professional activity. | FSES HE Requirements (BPC-3, UC-2,4), Criterion 5 RAEE (p 2.2) |
| LO10 | To demonstrate independent thinking, to function efficiently in command-oriented tasks and to have a high level of productivity in the professional (sectoral), ethical and social environments, to lead professional teams, to set tasks, to assign responsibilities and bear liability for the results of work. | FSES HE Requirements (PC-18,20,21,22,23, UC-1,4, BPC-2), Criterion 5 RAEE (p 1.6,2.3) coordinated with the requirements of the international standard EUR-ACE & FEANI |

Abstract

Key words: IRT-3M, thermal hydraulics, IRT-3M, IRT-T, modelling, Ansys.

Master's Thesis contains 89 pages, 28 figures, 31 tables, 23 references, 28 drawings.

The master's thesis has attempted to model thermal-hydraulic behavior of the fuel assembly of IRT-3M type of IRT-T reactor with various heat-conductivity surfaces.

Goal of the work is creation of proposals for modelling of water flowing in fuel assemblies of IRT-3M type for the purpose of heat-exchange intensification.

The first part describes performance of various heat-exchanging surfaces, thermal-hydraulic properties of IRT-T reactor's core.

The second part contains creation of geometrical models of IRT-3M fuel assemblies with various heat-exchanging surfaces. After this creation of numerical model of thermal-hydraulic model of IRT-3M assembly is presented. In the end of this part discussion of the modelling results is done.

Field of the application: training of students of 14.04.02 Nuclear physics and technology specialty.

Application area: Academic, Nuclear Industries.

Economic efficiency/significance of research outcomes: financial management analysis shown, that this model has high resource efficiency.

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Introduction

The main aim of nuclear research reactors is production of neutron fluxes of huge value. Huge gain in value of neutron flux in the whole energy spectrum can be achieved via increase in thermal power of reactor. However, growth of thermal power leads to amplified heat load on reactor core. This load is concentrated in fuel rods. Because of non-allowability of exceedance maximum permissible value characterizing heat duty, it's necessary in the case of increase in thermal power to take additional measures which can provide intensified heat removal from fuel rods.

One of such measure is implementation of intensification of heat exchange through implementation of passive heat removal methods. The main feature of such branch of methods is absence of necessity to use external energy source to keep up performance of heat-exchange intensifiers and absence of significant changes in active zone layout. In this work implementation of augmented heat exchanging surfaces of fuel assemblies is observed. The main impact of such surfaces is concentrated in shear layer with low heat conductivity properties. Application of augmented surfaces leads to destruction of boundary layer and increased heat-exchange.

Goal of the work: creation of computational model of water flowing in fuel assemblies of IRT-3M type for the purpose of further investigation of heat-exchange intensification.

Tasks:

- review of techniques of modification of heat-transfer surfaces;
- review of the effects leading to amplified heat-exchange in case of exploitation of turbulizers with characteristic sizes less than characteristic size of flowing channels
- review of factors affecting swirl structure of the flow, friction factor and heat exchange in channels with turbulizers;
- review of thermal-hydraulic characteristics of IRT-T;
- creation of computational models for modelling turbulent flow.

1 Literature Review

1.1 Review of techniques of modification of heat-transfer surfaces

Agree to modern views in the case of fully-turbulent flow effectiveness of application of swirling inserts overlapping width of the channel is significantly far below effectiveness of spiral finning with low height of flanges [1].

Application of turbulators with typical sizes less than cross dimensions of heat exchange channels (fig. 1, a, c, d) undermines usage of three mechanisms of heat transfer enhancement: additional eddy generation in near wall area by means of formation of separating zones in areas near to vortices, production of swirl motion of waver flow and effect of growth of heat transfer area because of heat transfer surface ribbing [1]. Use of turbulizers which don't have full thermal contact with heat transfer surface such as wire coil inserts, strip-swirls (fig. 1, e) is less efficient from thermal hydraulic point of view than spiral finning (fig. 1, b) unless they bear additional functions. These techniques are less efficient due to the fact that that such type of heat transfer augmentation exploits only two out of three mechanisms mentioned above.

On the contrast to techniques modification of heat-transfer surfaces the fact that heat-transfer enhancement techniques that don't have full contact with heat exchange surface can be seen as advantage because they don't change mechanical properties of apparatus in which they're applied. The absence necessity to introduce a change in fabrication process of apparatus can be also seen as advantage.

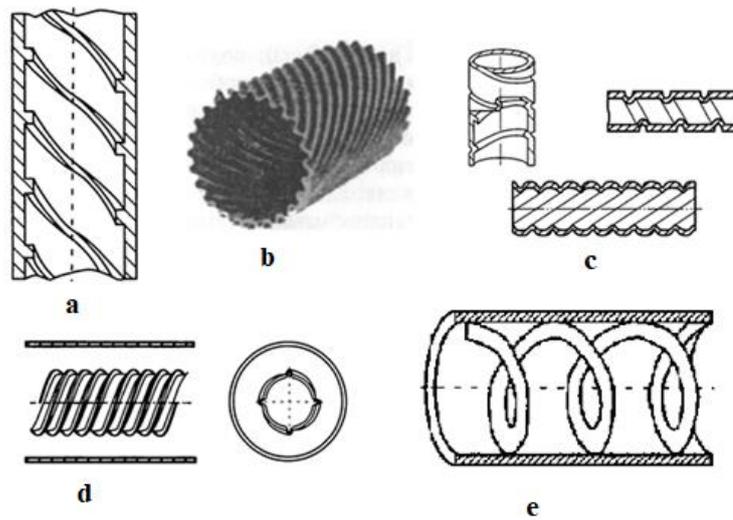


Figure 1 – Examples of different devices for swirling water flows in channels of different types: a – spiral ribbing, b – spirally corrugated tube, c – tube with single-wound helix, d – annular channel, consisting of smooth and spirally corrugated tubes, e – plated spiral insert.

Quite widespread way of intensification of heat transfer by repeated rib roughness (fig 1, b) undermines precedence of only one mechanism enhancement, namely, decrease of heat-transfer resistance through the destruction and turbulizing of viscous layer.

As a matter of tradition tape and screw inserts are claimed to be heat-transfer enhancers. Nevertheless, agree to work [1] application of tape (fig. 2, c) or screw inserts for heat-transfer enhancement purposes is not always effective. In the case of well-developed fully turbulent flows their effectiveness is significantly far below performance of turbulizers of fine shape. On the ground of analyzing huge amount of experimental data and generalizing equations for evaluation of heat-transfer and hydraulic resistance of tubes with tape and screw inserts authors of work [1] come to the conclusion that with a growth of Reynolds number and pitch of twist implementation of these techniques has a negative impact. The main reason for this is outrunning growth of hydraulic resistance in comparison with growth in heat-transfer.

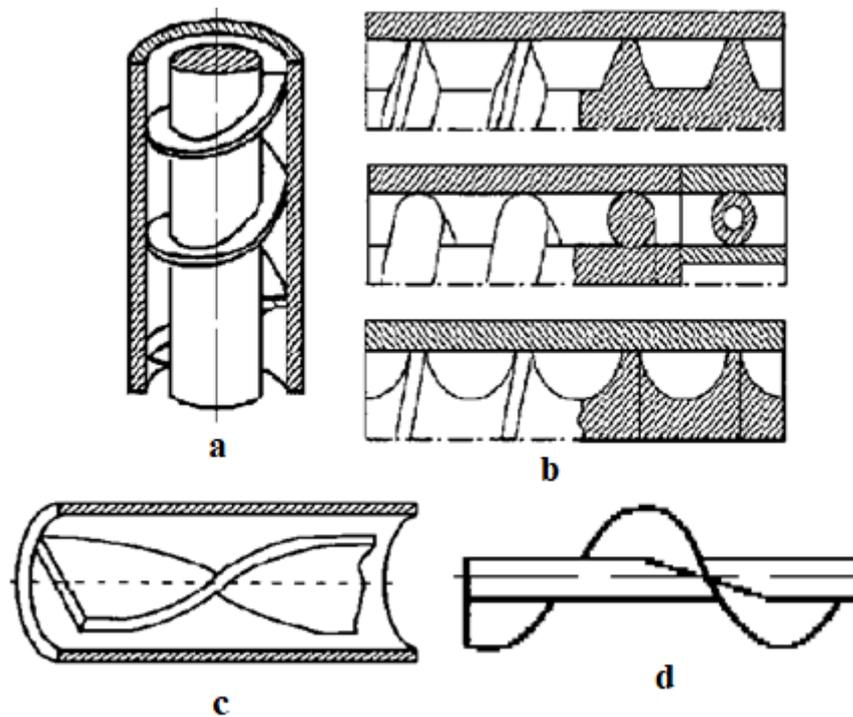


Figure 2 – Examples of fully locking flowing annular channels techniques: a – channel with single threaded tape, b – screw turbulizer, c – tape insert, d – screw

One of the main mechanisms of heat-transfer enhancement in the case of turbulent regime coolant flowing is additional turbulization of near wall layer, where the main heat resistance is located. Coating of streamlined protrusion on the heat-transfer surface (fins, coils, roughnesses etc.) is controlling action at the structure of near wall surface in the case of turbulent flowing of liquid.

1.2 Mechanism of impact of turbulators on near wall layer

By impact on eddy structure of near wall layer vortex generators can be seen as turbulizers since they provide periodical expansion, separation of flow and as a consequence of previous effects periodical renewal of boundary layer. All that leads to heat transfer enhancement.

Typical scene of vortex structure of turbulent flow corresponding to flowing round two dimensional ribs is presented on fig. 3 [2].

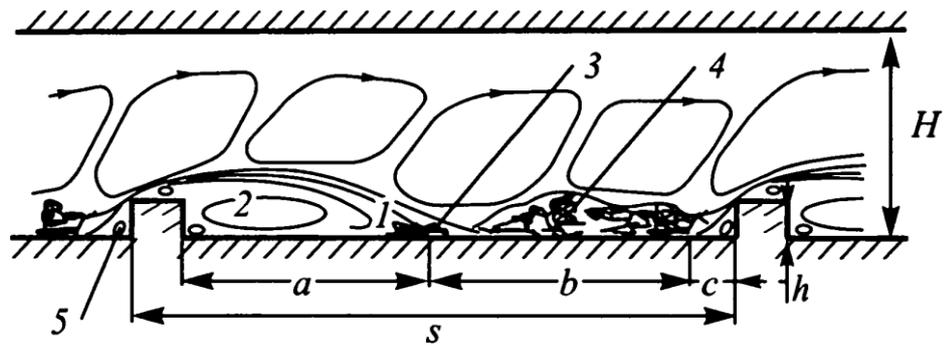


Figure 3 – Structure of turbulent flow during flow over of two-dimensional ribs: a, c – length of slipstream, b – area of reattachment and growth of boundary layer. 1 – shear layer, 2 - recirculation zone, 3 – zone of reattachment of shear layer, 4 – zone of relieving, 5 – secondary recirculation flow. S – pitch of ribs, h – height of rib, H – width of channel

Experimental studies of cross-flow of ribs made of high-drag bodies (ribs of rectangular cross-section, wired coils etc.), which are discussed in works [3, 4], showed that from both sides of ribs two distinctive separated flow regions are formed (a and c on fig. 3). Most of these regions are filled by zones with rotating recirculating flows. Length of slipstream zones a and c is unstable and falls in the range of half of the height of ribs. In the case of large of pitch S zone b is located between slippery zones, which includes reattachment area of growth of boundary layer.

Whole area after rib is divided in four zones: 1 – separated shear layer or free mixing layer, which is claimed to be the main source of turbulent energy in separation zone, 2 – recirculation zone with reversing unstable flow of liquid, 3 – zone of reattachment of shear layer, which is characterized by the maximum value heat exchange coefficient, 4 – zone of relieving, where removal from rib is accompanied by development of new boundary layer.

New separated shear layer is formed after separation from angular lip of drop. Down the stream shear layer strongly distorted, increases in cross-sectional direction and falls on the in the zone of reattachement. Part of the flow diverges in reversal direction and under impact of huge positive gradient of pressure it enters recirculation zone.

Researches of heat transfer in recirculating show, that local coefficients of heat transfer are greater than in undisturbed flow. Heat transfer in this zone can be divided in two parts: first, heat from wall is transferred by reversal flow, which, after flow makes a half turn, then transferred to the boundary with shear layer.

By means of flow visualization [5] it was established, that swirls which are formed in shear layer interact with surface in an unpredictable manner. It's thought that this interaction of swirls of shear layer leads to significant growth of heat-transfer in reattachment layer.

New shear layer starts to grow in the zone of relieving after reattachment zone inside reattached flow [5].

1.3 Factors that influence vortex structure of flow, pressure drop and heat-transfer in channels with vortices

Researches of cross-flow flanges of different shape on vortex structure of turbulent flows [3, 4] show, that it's better to avoid application flanges with harsh outlines (rectangles, triangles), due to the fact that during formation of transverse large-scale vortices in recirculating zones before flanges and after them dissipation of energy and production of turbulent energy are commensurable quantities. This leads to the high hydraulic losses. Thus, it's more efficient to apply smoothly outlined vortex generators, which produce much less pressure losses.

For the purpose of investigation of influence of geometrical parameters of different types of roughness on heat-transfer properties it would be good enough to observe research [6]. This research is compilation of data of 17 experimental study of heat-transfer properties of 7 types of tube surfaces. Basing on the derived data authors of this work make a conclusion that roughness type has greater impact on pressure drop mostly rather than on heat-transfer properties.

Work [7] is dedicated to the exploration of local heat-transfer after rapid widening of axis symmetrical channels. Results of this work show that heat-transfer

coefficient after rapid widening may become 3 or more times greater than heat-transfer coefficient for fully developed turbulent flow in smooth channel at the same Reynolds number.

Resultant drag of the row of cross-flow bodies depends on the pitch $t=S/h$ (fig. 3). Shielding effect appears in the case when for $t<10$. This effect is expressed in reduction of the total drag of flanges row in comparison with sum of drags of each isolated flange [8].

Summarizing data on influence of pitch of flowed row of bodies on heat-transfer in channels following conclusion can be done. Data for high-drag bodies shows that maximum of augmentation of heat transfer is achieved for the value of ratio of pitch to the height of bodies in the range from 8 to 10. Significant impact of the effect of reduction of the drag for the case of low pitches can't be achieved, because maximum of local heat-transfer corresponds to the location of separated stream. Therefore, it's necessary for the purpose of achieving maximal heat and power effectiveness of implementation of vortex generators it's necessary to make the pitch be slightly greater than length of separation zone a (fig. 3), that corresponds to the $t_0=t/h\approx 8-10$ [3, 9].

Basing on experimental research of the impact of wired coil on heat exchange in channel of circular cross-section [10] one may make a conclusion, that pitch of wired coil has a strong influence on the value of drag coefficient. At the same time influence of pitch of wire coil on the value of Nusselt number is insignificant. Results of his experiment are presented on fig. 5 and fig. 6. Sketch of coiling with mentioning of sizes is presented on fig. 4.

Thus, choice of the pitch should be based on the considerations related to minimization of thermal-hydraulic resistance in heat-exchanging channels. Therefore from graph presented on fig. 5 configuration WO2 leads to the least growth of drag resistance in the channels. However, the same configuration leads to the least growth of heat-exchanging properties. But as it was mentioned before difference of increase of thermal properties for different configurations of wired coil is insignificant.

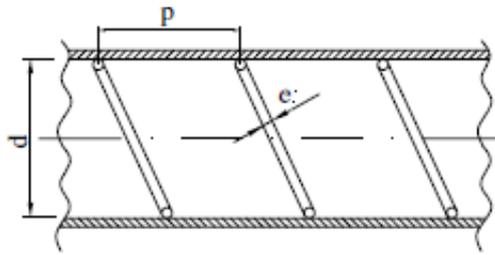


Figure 4 – Sketch of wire coil

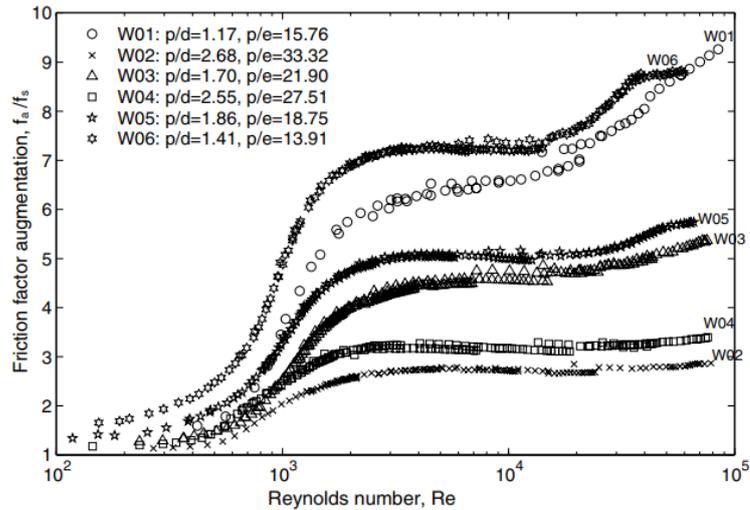


Figure 5 – Dependence of friction factor on Reynolds number in a case of different configurations of coiling, where p – pitch, d – internal tube diameter

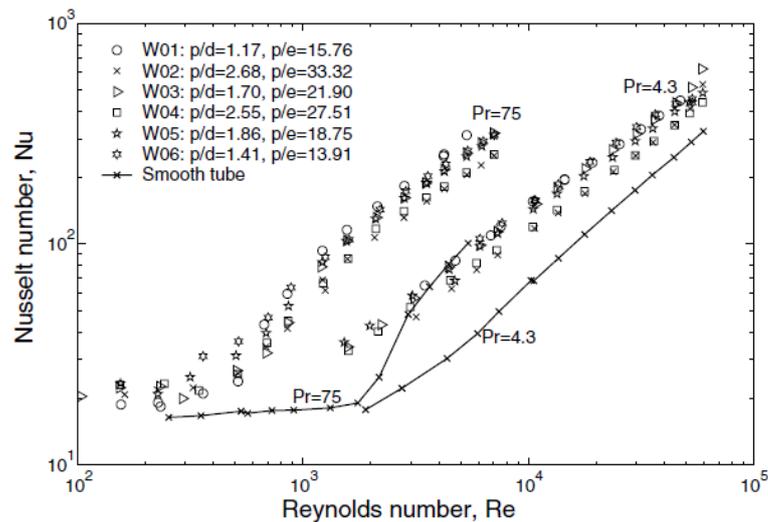


Figure 6 – Dependence of Nu on Re in a case of different configurations of coiling, where p – pitch, d – internal tube diameter

Heat-transfer in a case of different Reynolds number for the flow of water in spirally corrugated tubes was investigated in [12]. Sketch of this tube is shown on fig. 7. This work contains equations and graphs, characterizing pressure drops and augmentation of heat-transfer for 10 different configurations.

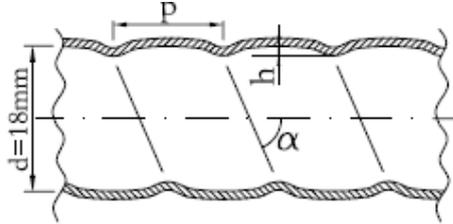


Figure 7 – Sketch of a single-start corrugated tube

Dependence of friction factor on the value of Reynolds number was derived through the measurements of heat drops in tube. Relative increase of Reynolds drag coefficient for different geometries were calculated basing on this dependence. Graphics that show this dependence are presented on figure 8. Basing on this dependence authors come to a conclusion that the main factor that affects value of friction factor in the case corrugated tube is value of φ coefficient: friction factor grows parallel to the friction factor:

$$\varphi = \frac{h^2}{p \cdot d}, \quad (1)$$

$$f_a / f_s = 1.53(\varphi)^{0.46} \text{Re}^{-0.16}, \quad (2)$$

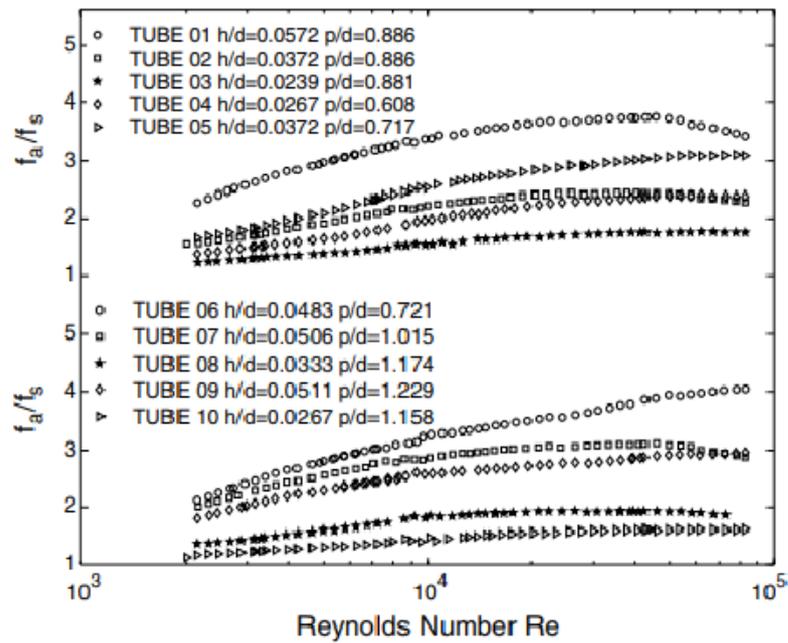


Figure 8 – Relative augmentation of friction factor in a case of different Reynolds numbers

Basing on compilation of huge amount of data from 17 sources for 7 different heat-transfer surfaces of tubes authors of work [13] derived equations approximating results of these researches for the Pr and Re numbers from 0.66 to 37.6 and from 5000 to 25000 respectively. Approximating equation was derived for different types of geometry spirally corrugated tubes, which characterized by the following geometrical parameters: $h/d=[0.01...0.2]$, $p/d=[0.01...0.2]$, $\alpha/90=[0.3...1]$. Authors of this work come to a conclusion that parameters characterizing shape of obstacle don't have on heat-transfer properties, due to the fact that this approximating equation doesn't contain parameters which characterize these properties:

$$\text{Nu}_a / \text{Nu}_s = \left\{ 1 + \left[2.64 \text{Re}^{0.036} (h/d)^{0.212} (p/d)^{-0.21} (\alpha/90)^{0.29} \text{Pr}^{0.024} \right]^7 \right\}^{1/7}, \quad (3)$$

Basing on compilation data of different researches of heat-transfer enhancement with a help of three mentioned above surfaces, authors of work [14] provide dependences for friction factor on Reynolds number, which presented on fig. 9 of surfaces. Basing on these dependences authors of this work make a

conclusion that in the case of fully turbulent flow relative increase of friction factor has the greatest value in the case of wire coil and the lowest value for corrugated tube.

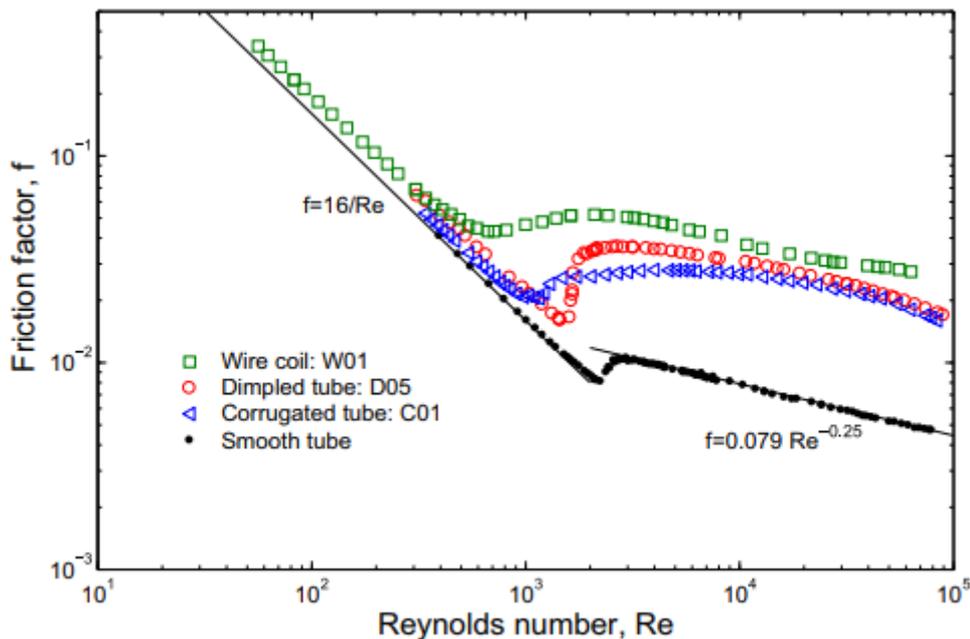


Figure 9 – Dependence of friction factor on Reynolds number for different types of surfaces

1.4 General description of IRT-T reactor

Nuclear research reactor IRT-T was constructed in 1967 and entered in operation in June 1967. Ten years after in June 1977 reactor was stopped for reconstruction due to progressive corrosion of reactor housing wear and aluminium heat exchangers. During reconstruction process new reactor housing made of steel 12X18H10T was installed, 1st and 2nd coolant circuits' equipment was completely replaced, CPS was modified to conform with safety standards requirements which were in force in that time. Equipment of 1st and 2nd circuits was installed in the quarters of newly built reactor's building. Start-up of reactor after reconstruction was conducted in 1984. Control and measurement apparatus of channel coolant flow rate, pressure and level of coolant in cooling circuits of reactor were replaced by new apparatus in 2000. Upgrading of reactor's control and protection system was done in

2005. During operation of IRT-T research reactor nuclear and radiological accidents with escape of radioactivity into environment have never occurred [15].

IRT-T is a pool-type nuclear research reactor with distilled light water used as moderator, coolant and top shield. Reactor is used in following fields of application: researches in solid state physics, neutron activation analysis of isotopic composition of materials, radionuclides production, neutron transmutation doping of silicon, neutron radiography. Students of Tomsk Polytechnic University have laboratory trainings at the reactor.

The longitudinal section of the reactor is shown on figure 10. The reactor core is located in a pool filled with demineralized water at a depth of 6.5 meters. The core vessel is made of aluminium alloy AD-1. The upper core vessel together with the support plate are mounted on a steel flange with a thickness of 29 mm. The flange is welded to the sheets of the built-in holding tank and rests on six column made of steel pipes $\text{\O}108$ mm. Column on the bottom are welded to the supporting steel plate with a thickness of 30 mm. Plate attached to the bottom of the tank by welding. To the core support plate is welded the lattice of channel CPS with thickness of 30 mm. The core support plate and the lattice of channel CPS protect the concrete under the tank bottom from radiation heating. In the places of contact of aluminium alloy parts with steel parts, titanium gaskets are installed to prevent corrosion of aluminium. The core vessel has 56 cells for the installation of fuel assemblies and beryllium blocks [15].

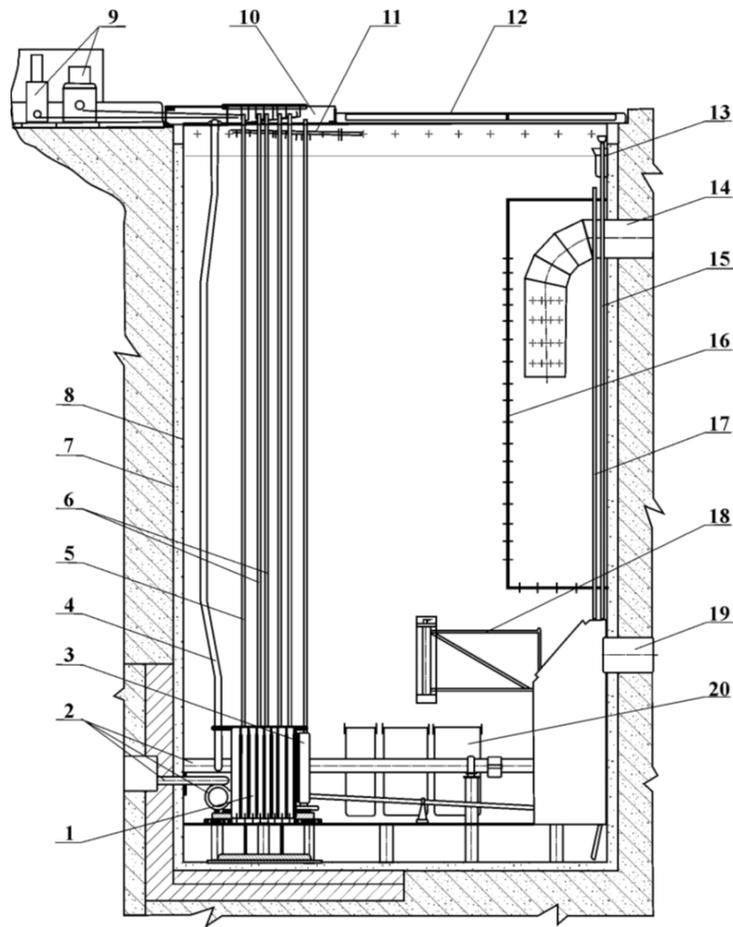


Figure 10 – Longitudinal sectional view of IRT-T reactor: 1 – core; 2 – horizontal experimental channel; 3 – generator of activity; 4 – vertical experimental channel; 5 – channel with a rod of CPS; 6 – central experimental channel; 7 – aluminium tank; 8 – stainless steel tank; 9 – drivers of the control rods; 10 – playground of CPS; 11 – spray thrower; 12 – transparent flooring; 13 – overflow funnel; 14 – pressure pipe; 15 – tube emptying; 16 – distributive tank; 17 – tube for a failure of the siphon; 18 – a device of FA transport ; 19 – suction pipe; 20 – interim storage facility

1.4.1 Active zone of IRT-T reactor

Active zone of the reactor is located into the pool filled with desalted at the deepness of 6.5 m (center of the active zone). Figure 11 depicts 3-D model of the active zone. Core tank is made of aluminium alloy AD-1. Upper tank of the zone together with separating grid is attached to the steel flange of the 29 mm thickness. Flange is welded to the plates of in-built hampering vessel and it's buttressed on six

pillars made of steel pipes of 108 mm diameter. Columns are welded to the core-support plate of 30 mm thickness. Plate is attached to the bottom of tank by welding. Lower grid of 30 mm thickness for control rods channels is attached to the plate from the top. Buttressing plate and lower grid protect concrete under bottom of the tank from radiation heating up. Titanium fillings are located in places of the contact of details made of aluminium alloys with steel details to avoid corrosion of the aluminium. Core tank contains 56 cells for installation of 56 cells and beryllium blocks [15].

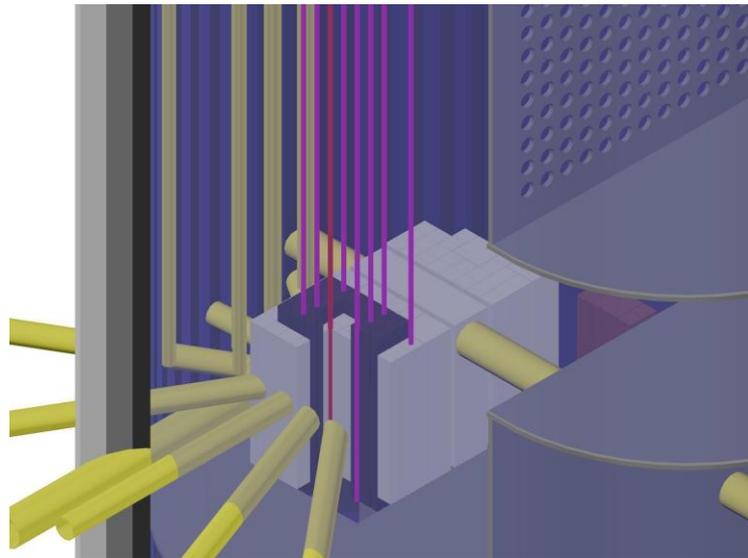


Figure 11 – 3-D model of the active zone of the IRT-T reactor with experimental channels

Fuel assemblies, beryllium blocks and neutron traps are installed on the distancing grid.

1.5 Characteristics of IRT-3M fuel assemblies

Fuel assemblies IRT-3M are used in active zone of IRT reactor. There are two types of IRT-3M assemblies: 6 tubes and 8 tubes assemblies. These fuel assemblies are comprised of fuel elements of rectangular cross-section with 1.4 thickness of walls. Thickness of shells made of aluminium alloy SAV-1 is 0.5 mm each.

Kernel is made of uranium dioxide in alumina matrix. Eliminator with 14 mm outer diameter is installed in 8 tubes fuel assembly. Control rod or experimental channel with outer diameter 28 mm is installed inside 6 tubes fuel assembly.

Design properties of IRT-3M are presented in table 1, table 2 contains geometrical parameter and mass of regular fuel assemblies. Fuel element number 8 instead of rectangular shape is circular. Radius of rounding of rectangular fuel elements is presented on fig. 12, on the outside its's 4.4 mm [15].

Table 1 – Design parameters of IRT-3M

| Parameter, unit | 8 tubes type | 6 tubes type |
|--|---------------------|--------------|
| Thickness of fuel kernel, mm | 0.4 | |
| Thickness of shell, mm | 0.5 | |
| Length of fuel layer, mm | 580 | |
| Fuel composition | UO ₂ +Al | |
| Material of shell | SAV-1 | |
| Concentration of U in fuel kernel, g/cm ³ | 1.07 | |
| Enrichment, % | 90±1 | |
| Content of U ²³⁵ in fuel assembly, g | 300 | 263.7 |

Table 2 – Sizes and masses of fuel rods in fuel assemblies IRT-3M

| Number of fuel rod | Length of fuel rod, mm | B, mm | b*, mm | M ₂₃₅ , g | M, kg |
|--------------------|------------------------|-------|--------|----------------------|-------|
| 1 | 721 | 69,4 | 66,5 | 59,4±3,5 | 0,75 |
| 2 | 650 | 62,5 | 59,6 | 53,2±3,2 | 0,60 |
| 3 | 650 | 55,6 | 52,7 | 47,0±2,8 | 0,53 |
| 4 | 650 | 48,7 | 45,8 | 40,9±2,5 | 0,46 |
| 5 | 650 | 41,8 | 38,9 | 34,7±2,1 | 0,39 |
| 6 | 650 | 34,9 | 32,0 | 29,5±1,7 | 0,32 |
| 7 | 650 | 28,0 | 25,1 | 22,5±1,3 | 0,26 |
| 8 | 650 | 21,1 | 18,3 | 13,8±0,8 | 0,15 |

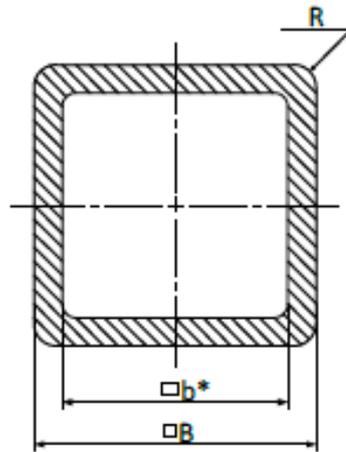


Figure 12 – Rectangular fuel rod

Six tubes fuel assembly IRT-3M is distinguished from 8 tubes fuel assemblies in following ways: alumina eliminator and two central fuel elements are removed. Channel for control rods is installed instead of them (fig. 13).

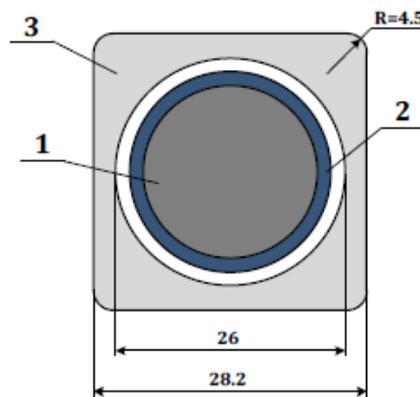


Figure 13 – Control rod channel with absorber pin in the center of 6 tubes fuel assembly: 1 – boron carbide, 2 – shell of pin, 3 – control rod channel

Key thermal-hydraulic features of reactor are given in table 3 [15].

Table 3 – Thermal-hydraulic features IRT-T reactor

| Parameter's name | Value |
|---|-------|
| Mean flow rate of coolant, m ³ /h | 650 |
| Maximal flow rate of coolant, m ³ /h | 900 |
| Flow rate of coolant through fuel assemblies | |

Continuation of table 3

| Parameter's name | Value |
|---|-------|
| – 8 tubes, m ³ /h | 33,2 |
| – 6 tubes, m ³ /h | 28,9 |
| Mean velocity of coolant, m/s | 3,0 |
| Temperature of coolant at the entrance of active zone, °C | 45,0 |
| Temperature drop of coolant in active zone, °C | 6,1 |
| Outlet pressure in active zone, MPA | 0,133 |
| Pressure drop in active zone, MPa | 0,037 |
| Mean thermal flux, kW/m ² | 290 |

Factory of origin has restrictions on exploitation of fuel assemblies IRT-3M, which consist of maximum values of operational parameters. These values are presented in table 4 [15].

Table 4 – Maximum values of operational parameters

| Parameter | Threshold value |
|---|-----------------|
| Coolant velocity, m/s | 5,3 |
| Threshold value of temperature on the surface of fuel rod, °C | 100 |
| Design parameter of thermal flux from fuel rod surface, MW/m ² | 0,8 |

1.6 Design parameters of IRT-3M fuel assemblies

Nominal values of design parameters which are specified by factory of origin (NZHK) for IRT-T reactor are presented in table 5.

Table 5 – Nominal values of design parameters

| Parameter | Value |
|---|----------|
| Standing of fuel assembly in reactors' core | Vertical |

Continuation of table 5

| Parameter | Value |
|---|-------------|
| Coolant | Water |
| Direction of coolant flow | Top-down |
| Entrance pressure in fuel assemblies, kPa | 135 – 170 |
| Pressure drop in active zone, kPa | 35 – 70 |
| Coolant velocity, m/s | < 5,3 |
| Temperature of coolant at the entrance of fuel assembly, °C | < 45 |
| Threshold value of temperature on the surface of fuel rod, °C | < 100 |
| Design parameter of thermal flux from fuel rod surface, MW/m ² | < 800 |
| Surface boiling of coolant on fuel elements | Not allowed |

In a case of other values characterizing mass flow rate of the coolant and it's temperature at the in inlet of fuel-assembly it's necessary to keep value of temperature of the cladding of fuel elements less than 100 °C [15].

In technical report for safety and security arrangements of IRT-T reactor further values of some parameters are mentioned:

- temperature of the coolant at the inlet of active zone, °C – 45;
- pressure at the outlet from active zone, kPa – 133;
- pressure drop in the active zone, kPa – 37.

1.6.1 Thermal-hydraulic characteristic of IRT-T reactor

Work [16] contains results of experimental determination of mass flow rate and velocity of coolant in clearances of IRT-3M fuel assembly in the case of 37 kPa pressure drop. Average velocity of the coolant in clearances of fuel assembly is 1.6 m/s. Cooling of fuel elements and reflector of active zone is done by water of

reactors' pool. It's pumped through clearances between fuel elements and clearances between beryllium blocks.

Hydraulic characteristic of 8 and 6 tubes IRT-3M fuel assemblies (values of water velocities in clearance between fuel elements and flow rates through fuel assemblies) at the pressure drop 37 kPa are presented in table 6. Numbering starts from outer fuel element to inside fuel element. Values of velocity of coolant were determined experimentally, values of flow rate are calculated [16].

Table 6 – Hydraulic characteristic of fuel assemblies at the pressure drop 3.4 mAq.

| Parameter | Value | |
|--|---------|---------|
| | 8 tubes | 6 tubes |
| Velocity in clearance, m/s: clearance between fuel assemblies | 1.96 | 1.96 |
| Clearance between 1 and 2 fuel elements | 1.74 | 1.74 |
| Clearance between 2 and 3 fuel elements | 3.00 | 3.00 |
| Clearance between 3 and 4 fuel elements | 3.12 | 3.12 |
| Clearance between 4M and 5 fuel elements | 1.99 | 1.99 |
| Clearance between 5 and 6 fuel elements | 3.50 | 3.50 |
| Clearance between 6 and 7 fuel elements | 3.42 | — |
| Clearance between 7 and 8 fuel elements | 3.16 | — |
| Clearance between 8 fuel rod and eliminator | 3.40 | — |
| Clearance inside eliminator | 0.61 | — |
| Clearance between 6 fuel rod and control rod channel | — | 3.42 |
| Clearance between housing and control rod | — | 1.38 |

Due to the high value of inhomogeneity of allocation of materials in the active zone and unevenness of energy radiation from fuel elements surfaces, average heat flux from surface of fuel elements is about $\sim 220 \text{ kW/m}^2$, meanwhile maximum values may be significantly greater.

2 Thermal hydraulic modelling of the 8 tubes fuel assembly of IRT-3M

type

2.1 RANS

Nowadays Reynolds decomposition of turbulent values in fluctuating and steady mean components is the main approach for solving continuity and Navier-Stocks equations for modelling turbulent flows [17]:

$$\varphi(t) = \Phi + \varphi'(t), \quad (4)$$

$$\Phi = \frac{1}{\Delta t} \int_0^{\Delta t} \varphi(t) dt, \quad (5)$$

where φ – turbulent value;

Φ – time averaged value of φ ;

φ' – fluctuating value, mean value of which equals 0.

After applying Reynolds decomposition Navier-Stocks and discontinuity equations will have following appearance [17]:

$$\text{div}(\mathbf{U}) = 0, \quad (6)$$

$$\begin{aligned} \frac{\partial U}{\partial t} + \text{div}(U\mathbf{U}) = & -\frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \cdot \text{div}(\text{grad}(U)) + \\ & + \frac{1}{\rho} \left[\frac{\partial(-\rho \overline{u'^2})}{\partial x} + \frac{\partial(-\rho \overline{u'v'})}{\partial y} + \frac{\partial(-\rho \overline{u'w'})}{\partial z} \right], \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{\partial V}{\partial t} + \text{div}(V\mathbf{U}) = & -\frac{1}{\rho} \frac{\partial P}{\partial y} + \nu \cdot \text{div}(\text{grad}(V)) + \\ & + \frac{1}{\rho} \left[\frac{\partial(-\rho \overline{u'v'})}{\partial x} + \frac{\partial(-\rho \overline{v'^2})}{\partial y} + \frac{\partial(-\rho \overline{v'w'})}{\partial z} \right], \end{aligned} \quad (8)$$

$$\begin{aligned} \frac{\partial W}{\partial t} + \text{div}(W\mathbf{U}) = & -\frac{1}{\rho} \frac{\partial P}{\partial z} + \nu \cdot \text{div}(\text{grad}(W)) + \\ & + \frac{1}{\rho} \left[\frac{\partial(-\rho \overline{u'w'})}{\partial x} + \frac{\partial(-\rho \overline{v'w'})}{\partial y} + \frac{\partial(-\rho \overline{w'^2})}{\partial z} \right], \end{aligned} \quad (9)$$

where U, V, W – average x, y, z velocities respectively, m/s;

\mathbf{U} – vector of average x-velocity;

t – time, s;

ρ – density, kg/m³;

P – pressure, Pa;

ν – kinematic viscosity, m²/s;

u', v', w' – fluctuating values of x, y, z velocities respectively, m/s.

In comparison to Navier-Stokes equations for instantaneous values of variables, right part of the system contains third members, which contains derivatives fluctuating values of velocities. These members are related to convective transport of fluctuating values of momentum through turbulent vortices. These members are called turbulent stresses. These shear stresses are comprised of 3 normal stresses and 3 shear:

$$\tau_{ij} = -\overline{\rho u'^2} \quad (10)$$

where j – direction of stress;

i – axis to which plane where stress acts is perpendicular.

For scalar values such as temperature transport equations will have following form [17]:

$$\begin{aligned} \frac{\partial \Phi}{\partial t} + \text{div}(\Phi \mathbf{U}) = & -\frac{1}{\rho} \text{div}(\Gamma_{\Phi} \text{grad}(\Phi)) + \\ & + \frac{1}{\rho} \left[\frac{\partial(-\overline{\rho u' \varphi'})}{\partial x} + \frac{\partial(-\overline{\rho v' \varphi'})}{\partial y} + \frac{\partial(-\overline{\rho w' \varphi'})}{\partial z} \right], \end{aligned} \quad (11)$$

One of approaches in description of turbulent stresses is Boussinesq expression. Boussinesq proposed that turbulent stresses are proportional to the average velocity:

$$\tau_{ij} = -\overline{\rho u'_i u'_j} = \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \rho k \delta_{ij}, \quad (12)$$

where δ_{ij} – Kronecker delta, $\delta_{ij} = 1$ if $i = j$ and $\delta_{ij} = 0$ if $i \neq j$.

The main disadvantage of RANS models comes from the isotropic assumption of energy distribution in Boussinesq expression, because in reality it's highly anisotropic. Because heat and momentum or mass transport is also done through vortex mixing it's possible to assume that values of coefficients of turbulent transport are close to values of turbulent viscosity. This assumption is called Reynolds analogy. It's expressed through Prandtl/Schmidt number:

$$\sigma_t = \frac{\mu_t}{\Gamma_i} \quad (13)$$

Thus new system of equations which was derived through Reynolds averaging is not closed because of additional members consisting of turbulent stresses. To solve this system of equations it's necessary to add at least equations for new members of equations. There's a large variety additional equations which differ by the view of additional equations. K- ϵ , k- ω and combining them SST model are the most widespread approaches to construct these additional equations [17].

2.2 k- ϵ model

In this model two additional equations are added to the derived system of discontinuity and Navier-Stocks equations: equation for description of turbulence energy per mass (k) and rate of dissipation of turbulent energy per mass (ϵ). These equations are also derived for mean values of these variables through RANS method.

Value of turbulence viscosity coefficient is calculated in the following form:

$$\mu_t = C \rho \mathcal{G} l = \rho C_\mu \frac{k^2}{\epsilon}, \text{ Pa} \cdot \text{S} \quad (14)$$

где \mathcal{G} – velocity scale;

l – length scale;

C_μ – dimensionless constant.

Governing equation for k is derived from initial Navier-Stocks equations. The model's transport equation in contrast to governing equation contains special

modelled turbulent transport term. Equation for ε can be also derived from initial equations but it won't be enclosed. The model equation for ε assumes that production and destruction terms in k and ε equations are directly proportional to each other, so that when k term grows rapidly ε term also does so and vice versa. Constants $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are induced into equations to make this proportionality correct. These modellings are resulted in the following form of equations [17]:

$$\rho \frac{\partial k}{\partial t} + \rho \operatorname{div}(k\mathbf{U}) = \operatorname{div} \left[\frac{\mu_t}{\sigma_k} \operatorname{grad}(k) \right] + 2\mu_t S_{ij}^2 - \rho\varepsilon \quad (15)$$

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho \operatorname{div}(\varepsilon\mathbf{U}) = \operatorname{div} \left[\frac{\mu_t}{\sigma_k} \operatorname{grad}(\varepsilon) \right] + C_{1\varepsilon} \frac{\varepsilon}{k} 2\mu_t S_{ij}^2 - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} \quad (16)$$

The standard k- ε model employs values for the constants that are derived through comprehensive data fitting for a wide range of turbulent flows, their values are presented in the following table.

Table 7 – Values of constants [17]

| | | | | |
|----------------|-------------------|-----------------------------|---------------------------|---------------------------|
| $C_\mu = 0.09$ | $\sigma_k = 1.00$ | $\sigma_\varepsilon = 1.30$ | $C_{1\varepsilon} = 1.44$ | $C_{2\varepsilon} = 1.44$ |
|----------------|-------------------|-----------------------------|---------------------------|---------------------------|

This model provides certainty of calculations which is sufficient for engineering calculations. Still experience of many calculations of separate turbulent flows after blunt bodies shows that turbulent models based on the dissipation rate ε predict place of the beginning of separation very far in the downstream from real points which are observed in experiments. Moreover calculated sizes of recirculating zone and intensity of movement in this model are significantly undervalued [18].

2.3 k- ω and SST models

The most widespread alternative for k- ε system of equations among two equations approach is k- ω system of equations. It's claimed that it provides the best results in terms of concordance with experimental data on place of flow separation

zones [18]. This model uses turbulent frequency variable ω instead of ε as the second variable. This variable is the opposite value of vortex lifetime:

$$\omega = \frac{\varepsilon}{k}, \text{ s}^{-1} \quad (17)$$

If ω variable is applied than equation for turbulent viscosity has the following view:

$$\mu_t = \frac{\rho k}{\omega}, \text{ Pa} \cdot \text{S} \quad (18)$$

Models' transport equations for k and ω :

$$\rho \frac{\partial k}{\partial t} + \rho \text{div}(k\mathbf{U}) = \text{div} \left[\mu + \frac{\mu_t}{\sigma_k} \text{grad}(k) \right] + 2\mu_t S_{ij}^2 - \frac{2}{3} \rho \frac{\partial U_i}{\partial x_j} \delta_{ij} - \beta \cdot \rho k \omega, \quad (19)$$

$$\rho \frac{\partial \omega}{\partial t} + \rho \text{div}(\omega\mathbf{U}) = \text{div} \left[\mu + \frac{\mu_t}{\sigma_\omega} \text{grad}(\omega) \right] + \gamma_1 \left(2\rho S_{ij}^2 - \rho \omega \frac{\partial U_i}{\partial x_j} \delta_{ij} \right) - \beta_1 \cdot \rho \omega^2, \quad (20)$$

Values of models' constants are presented in the following table:

Table 8 – Constants for k - ω model [17]

| | | | | |
|--------------------|-------------------|------------------------|-------------------|------------------|
| $\gamma_1 = 0.553$ | $\sigma_k = 2.00$ | $\sigma_\omega = 2.00$ | $\beta_1 = 0.075$ | $\beta^* = 0.09$ |
|--------------------|-------------------|------------------------|-------------------|------------------|

The main advantage of such models is good results in boundary layer of near-wall area. However, experience shows that this model produces badly consistent with experiment results in the free stream zone at a remove from boundary layer. Thus, k - ω model can't be fully adequate substitute for k - ε model [19]. Shear Stress Transport model is the hybrid model which combines in itself equations for k - ε and k - ω models. Each equation model activates in a zone where it produces the most reliable results. Equation for k stays the same as in k - ω model. Equation for ω has the following form:

$$\begin{aligned} \rho \frac{\partial \omega}{\partial t} + \rho \text{div}(\omega\mathbf{U}) = & \text{div} \left[\left(\mu + \frac{\mu_t}{\sigma_\omega} \right) \text{grad}(\omega) \right] + \\ & + \gamma_2 \left(2\rho S_{ij}^2 - \frac{2}{3} \rho \omega \frac{\partial U_i}{\partial x_j} \delta_{ij} \right) - \beta_2 \cdot \rho \omega^2 + 2 \frac{\rho}{\sigma_{\omega,2} \omega} \cdot \frac{\partial k}{\partial x_k} \cdot \frac{\partial \omega}{\partial x_k} \end{aligned} \quad (21)$$

Constants for this model are calculated in the following form:

$$\Phi_3 = F_1\Phi_1 + (1 - F_1)\Phi_2, \quad (22)$$

where Φ_1 and Φ_2 – coefficients from k- ω and k- ϵ models, respectively;
 F_1 – blending function.

2.4 Geometrical model

Practical part starts with construction of the 3D-model of fuel assembly. Each part of the assembly was constructed separately basing on the drawings of fuel assembly which were provided by NZHK. Initially geometrical model is highly detailed representation of the fuel assembly. Appearance of the parts of the assembly and the assembly itself are presented on f

Figure-18. Fuel elements part consists of 16 bodies: 8 fuel parts and 8 claddings.

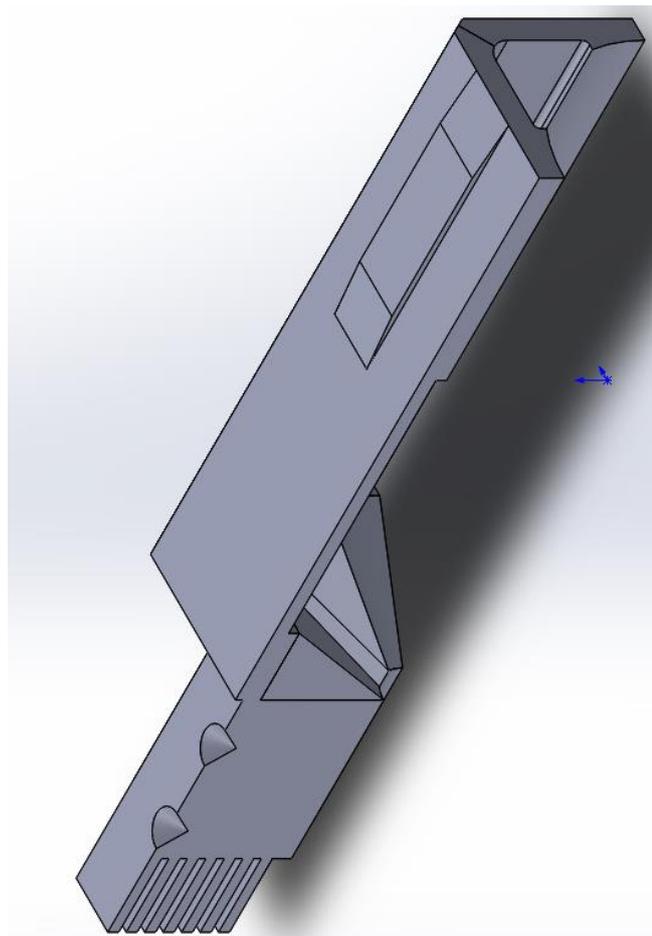


Figure 14 – Upper-end plug

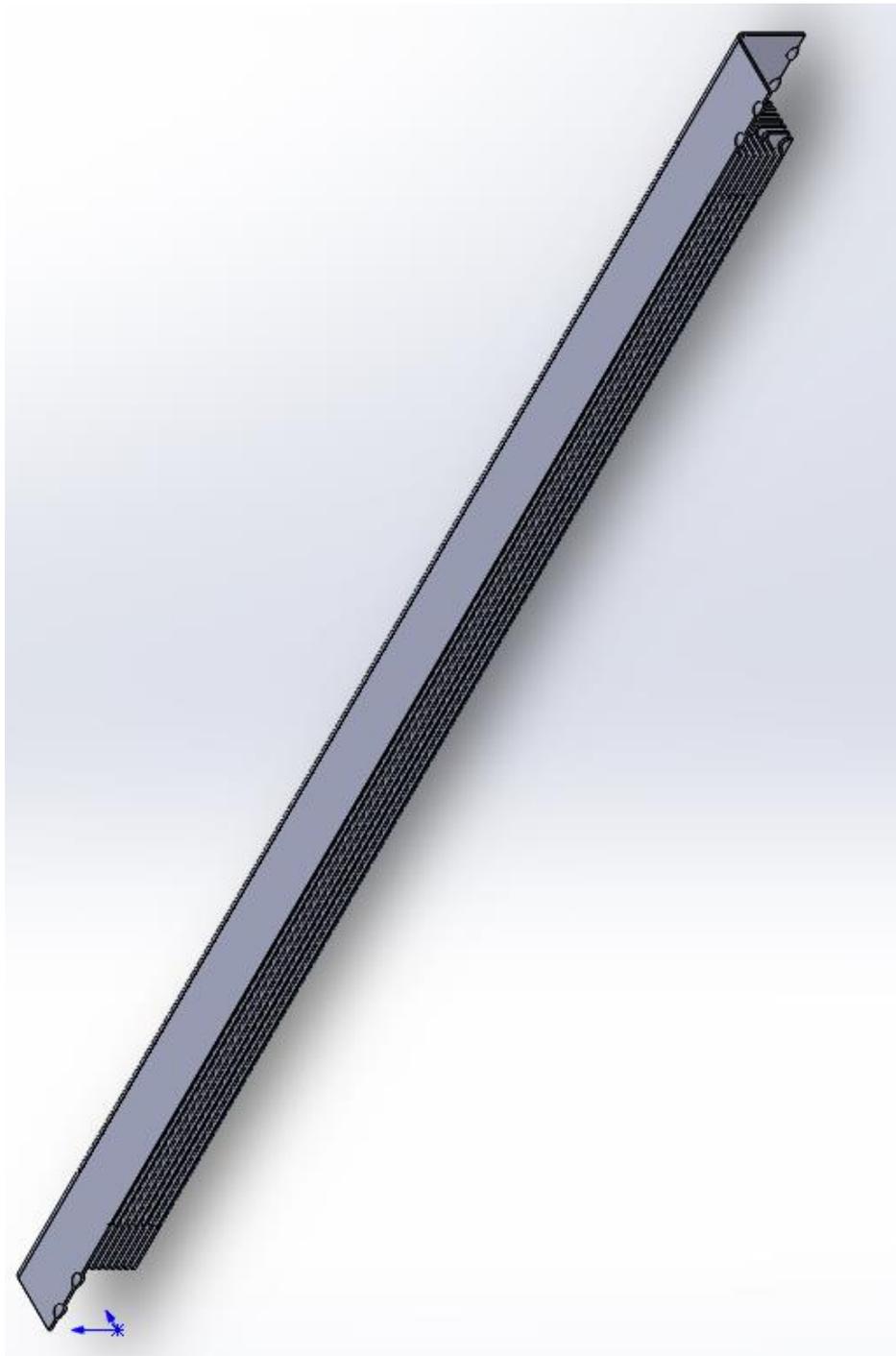


Figure 15 – Fuel elements



Figure 16 – Displacer

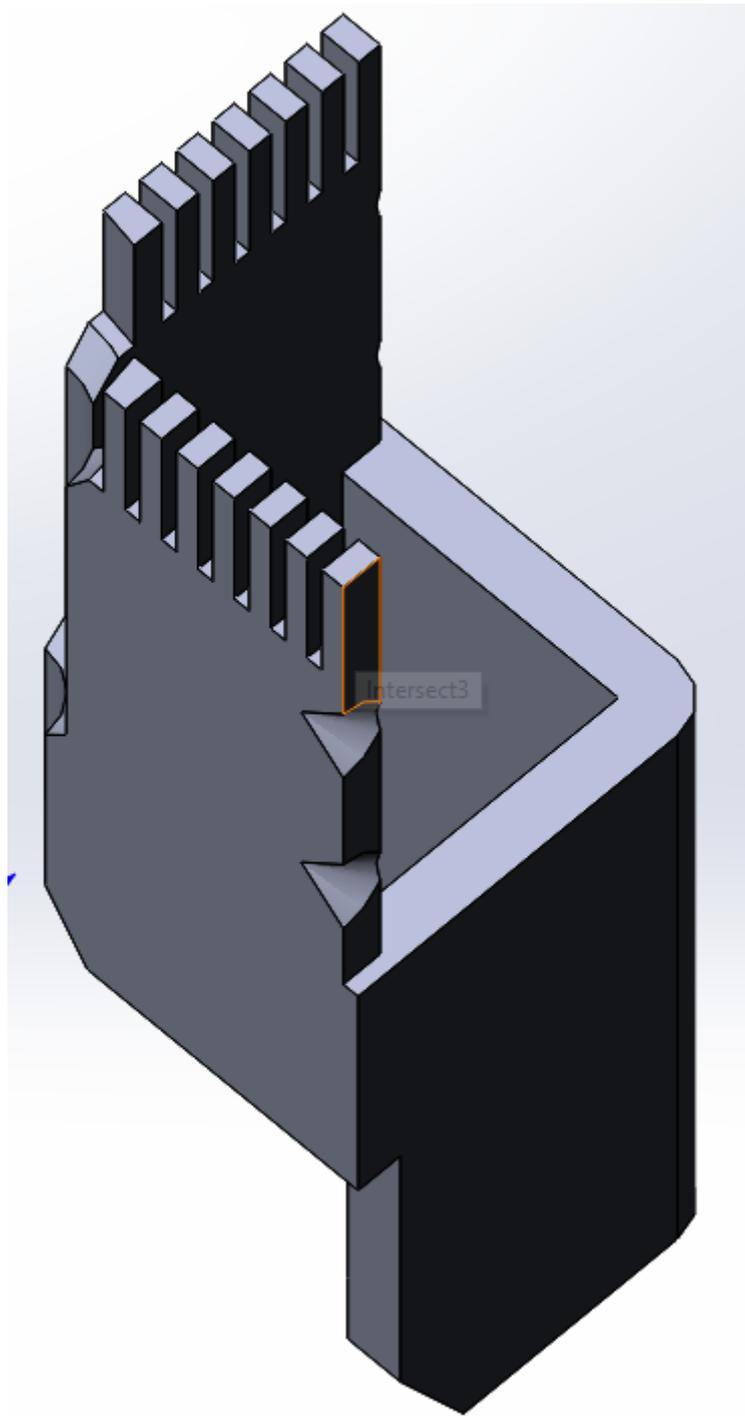


Figure 17 – Bottom nozzle

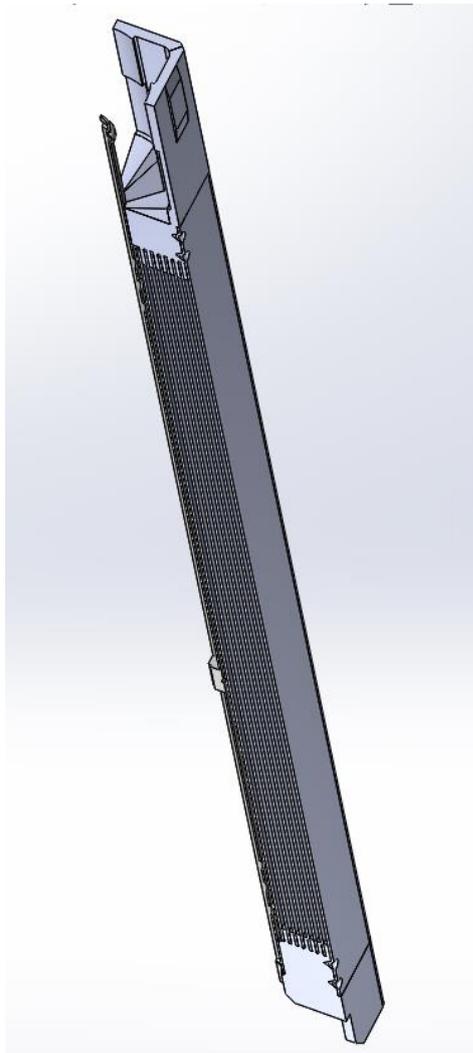


Figure 18 – IRT-3M fuel assembly

Initially it was planned to conduct modelling with a help of commercial version of Ansys-CFX. Due to the lockdown during the work on master thesis only student's version of Ansys-CFX was available, which has strict restrictions on the number of surfaces for geometrical model. That's why it was necessary to drastically simplify initial geometrical model. Epim necessity for simplification lead to the elimination of the bottom-nozzle part and also to the simplification of the geometry of the upper-end plug.

Simplification of the head part of the fuel assembly represents from itself elimination of all small protruding parts except the main hydraulic obstacle. The main hydraulic obstacle is part of the upper end plug which has function of fixation of the fuel elements. The final appearance of the upper-end plug is presented on the

figure 19. Also final geometrical part contains water which covers whole fuel assembly.

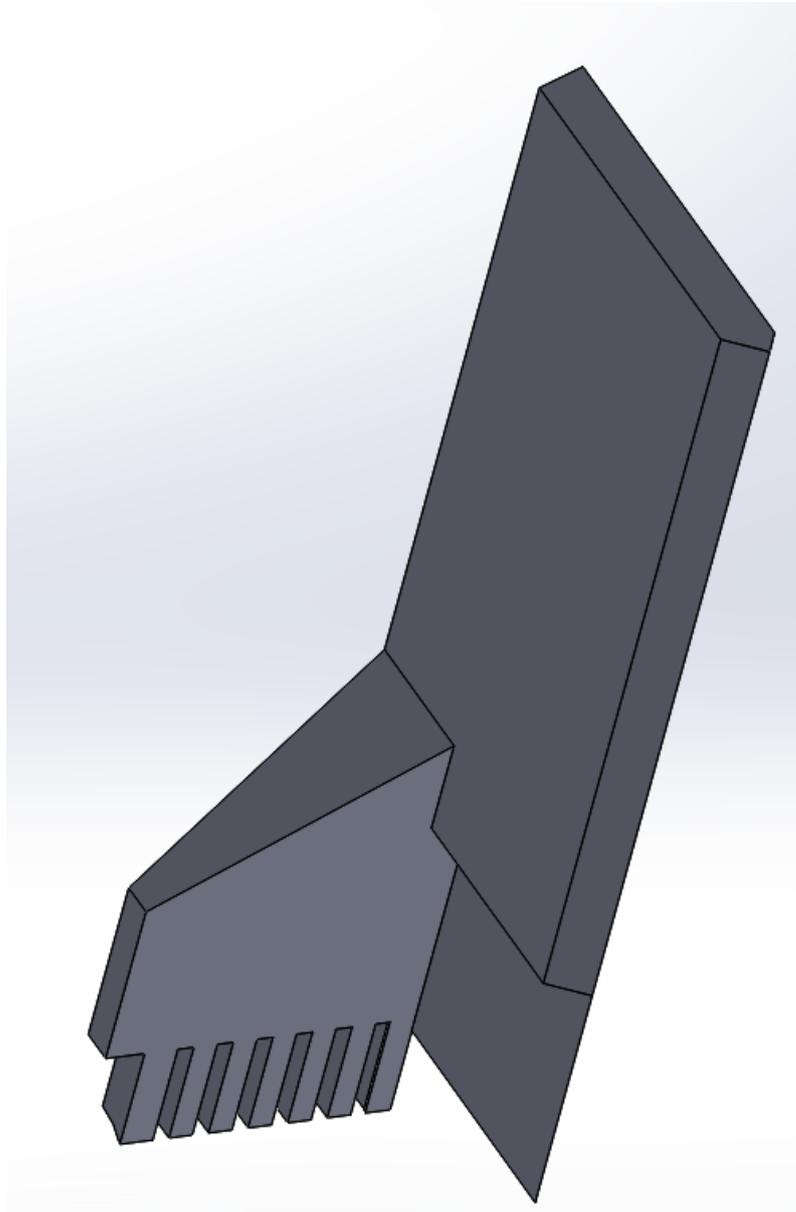


Figure 19 – Simplified geometry of the upper-end plug

Basing on the model of fuel assembly with smooth heat-exchanging surface, models with modified heat-exchanging surfaces were made. Appearance of their heat-exchanging surfaces is presented on figure 20 and 21.

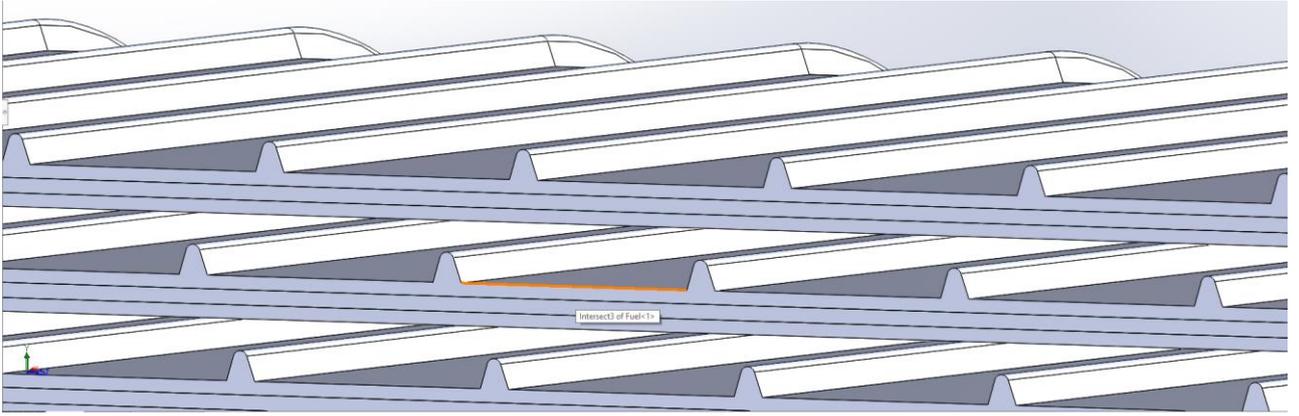


Figure 20 – Ribbed heat-exchanging surface

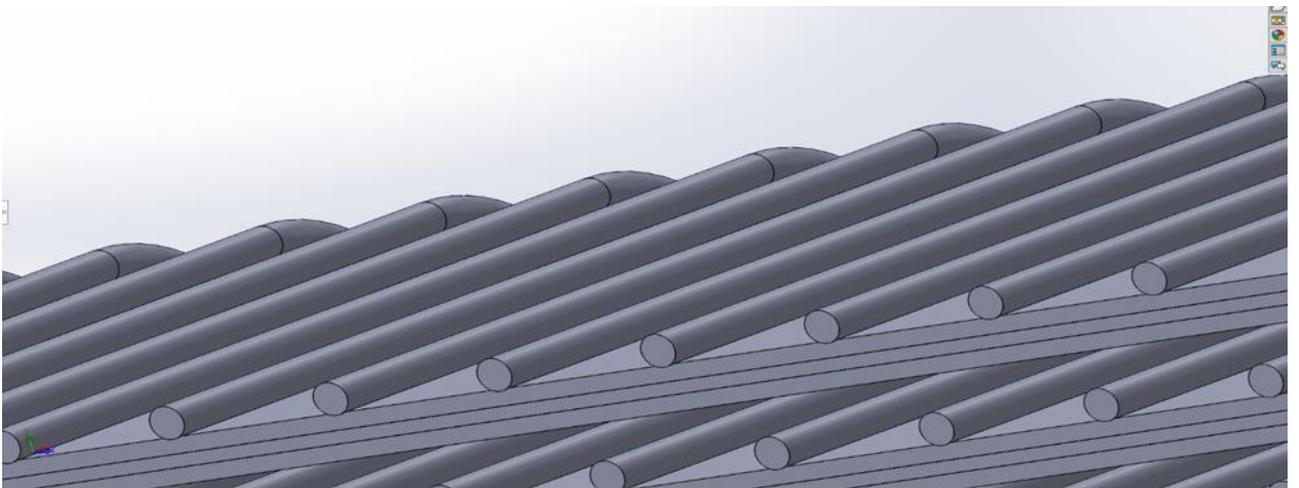


Figure 21 – Wire-coil heat-exchanging surface

To follow recommendations which were presented above first of all it was necessary to calculate hydraulic diameters for channels which are located in a space between fuel elements. These values are presented in table 9.

Table 9 – Hydraulic diameters

| Location | Values of hydraulic diameters, mm |
|--|-----------------------------------|
| 1-2 | 4,17 |
| 2-3 | 4,19 |
| 3-4 | 4,22 |
| 4-5 | 4,26 |
| 5-6 | 4,31 |
| 6-7 | 4,38 |
| 7-8 | 6,75 |
| Channel between 8 th FE and displacer | 4,3 |

After obtaining values of hydraulic diameters it becomes possible to calculate pitch between ribs for corrugated configuration of heat exchanging surfaces of fuel elements. Obtained values for pitches and height of ribs for each intertubular space are presented in table 10. Also using this data recommendation for wired coil geometry were obtained. Pitch and diameters for wired coils are provided in table 11.

Table 10 – Data on pitch and height of ribbed geometry

| Location | s, mm | h, mm |
|--------------------------------------|--------|-------|
| 1-2 | 7.008 | 0.238 |
| 2-3 | 7.044 | 0.239 |
| 3-4 | 7.089 | 0.241 |
| 4-5 | 7.150 | 0.243 |
| 5-6 | 7.234 | 0.245 |
| 6-7 | 7.359 | 0.250 |
| 7-8 | 11.341 | 0.385 |
| Channel between 8th FE and displacer | 7.224 | 0.245 |

Table 11 – Data on pitch and radius of wired coil geometry

| Location | Pitch, mm | R, mm |
|--------------------------------------|-----------|-------|
| 1-2 | 11.180 | 0.168 |
| 2-3 | 11.237 | 0.169 |
| 3-4 | 11.309 | 0.170 |
| 4-5 | 11.406 | 0.171 |
| 5-6 | 11.540 | 0.173 |
| 6-7 | 11.739 | 0.176 |
| 7-8 | 11.524 | 0.271 |
| Channel between 8th FE and displacer | 49.044 | 0.74 |

Due to the symmetry of geometrical model final problem contains only 1/8 part of the whole assembly. This also leads to the simplification of the problem. The reduction of the geometry doesn't make the problem coarser and at the same time it's beneficial in terms of reduction of the necessary computational power for solving the problem. Fuel elements and the lower part of displacer are covered by the same water body. The final geometrical model is presented on figure 22 and 23.

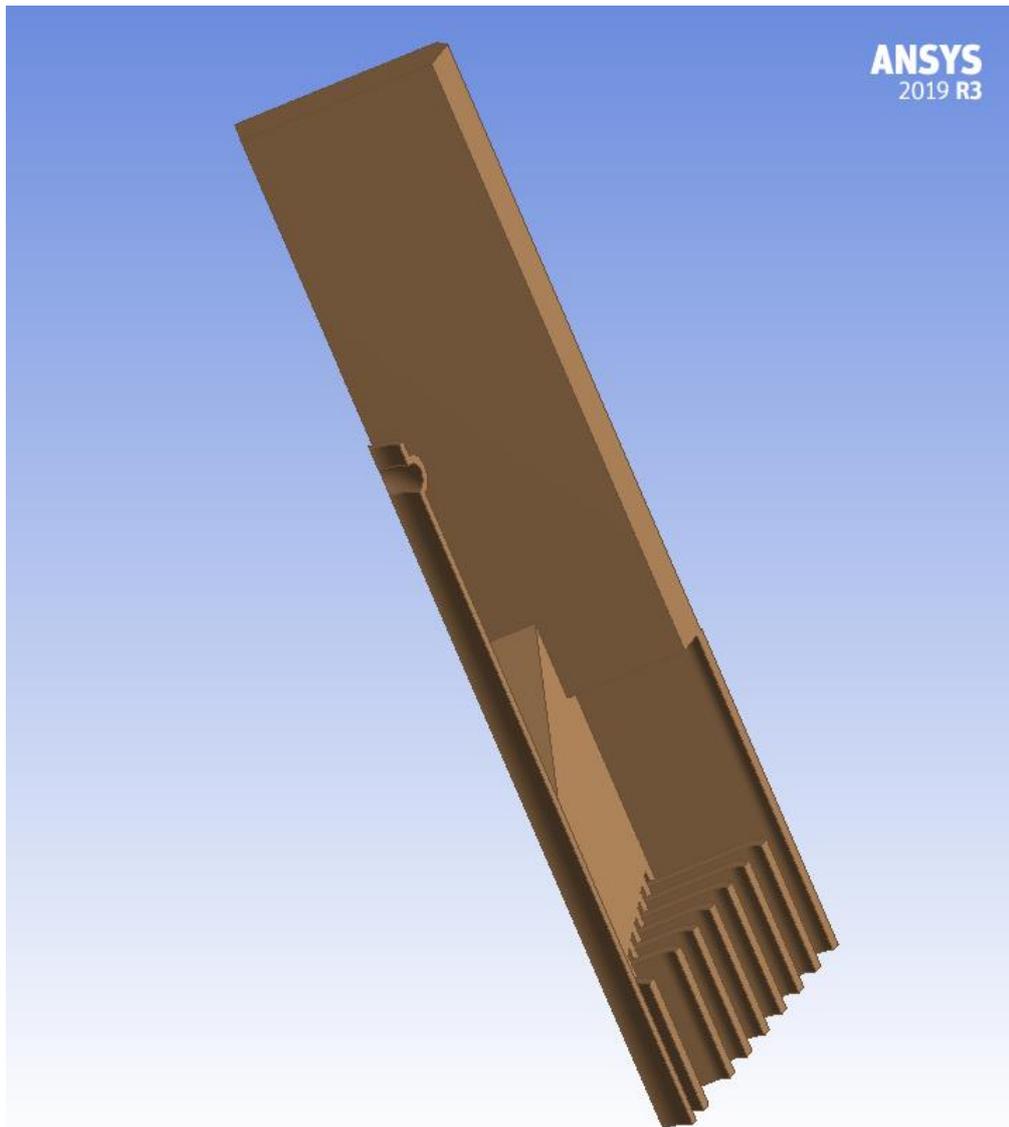


Figure 22 – Upper part

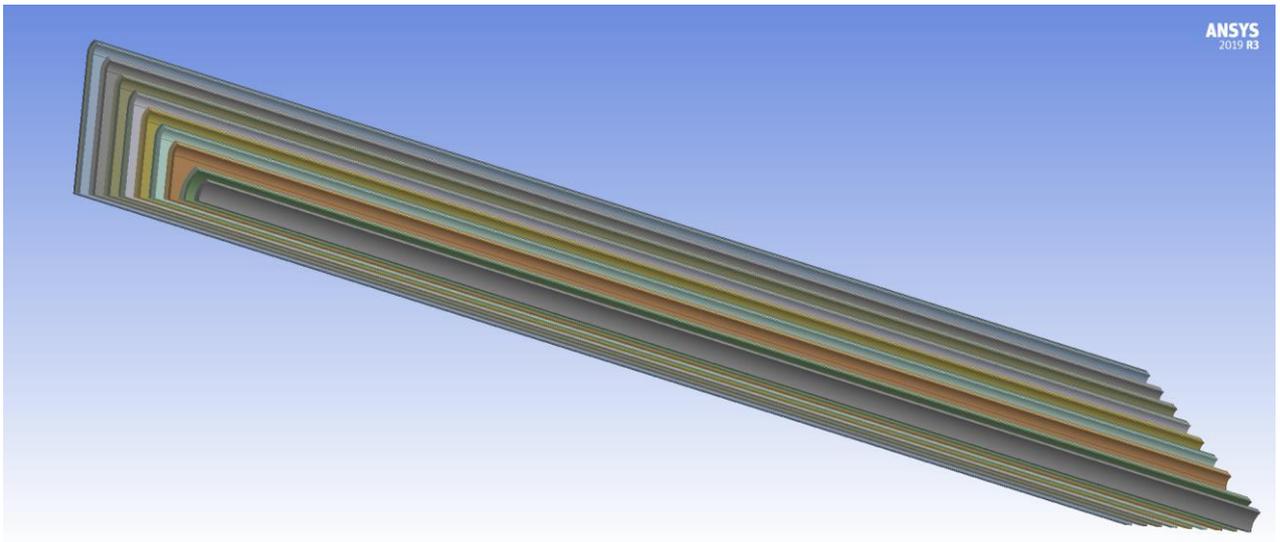


Figure 23 – Fuel elements part

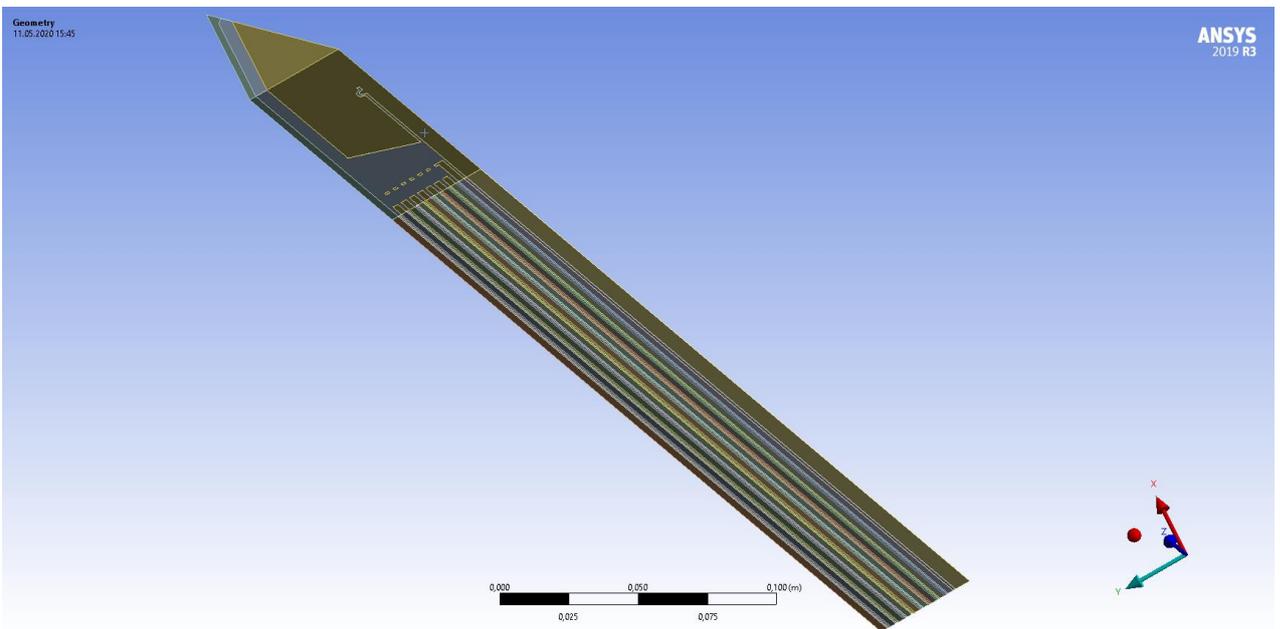


Figure 24 – Final geometrical model

Upper-part consists of the number of solid bodies which were united into one by the Boolean operation. Border for the upper is the top surface of the fuel part of fuel elements. Bodies which were included into the upper part: top parts of cladding, upper-end plug and the top part of the displacer. This was made due to the following considerations: all parts are made of the same material, they don't produce heat. But the main consideration is that it's necessary to split the water part in the way which will be elaborated in the part related to meshing. Water flowing along fuel assembly

is represented by the upper part, which consists of the 2 bodies, and by part made of 10 bodies which covers heat producing solid part.

2.5 Meshing

Ansys-CFX Meshing module provides possibility for creation of the automatic mesh. However, for heat-conductivity problem this mesh is of the poor quality. For instance, in the current work automatic mesh engine generated mesh in which nodes of water part, which covers fuel part, nodes for cladding and fuel didn't connect. This leads to the poor quality interpolation results. However, for the upper part of the model automatic engine produced mesh of the good quality.

Thus, it's necessary to set the mesh for the water around cladding, cladding and fuel manually. Two main factors affect further considerations on meshing: restrictions of the student's version (no more than 512000 of nodes/elements) and precision of the results.

To generate mesh for all bodies below the upper part of the model Sweeping method together with face sizing option was used. Sweep number divisions was set to 100. Due to the fact that all bodies in this area are symmetrical this method is suitable for mesh generation. Also size of the mesh elements was set to the inflation on the borders between bodies. This was done to get the highest precision of the modelling in the area near to the cladding of the elements, because all safety requirements are applied to this region. Resultant mesh for bodies below top part is depicted on figure 25. Mesh for whole model consists of 286503 nodes and 274507 elements.

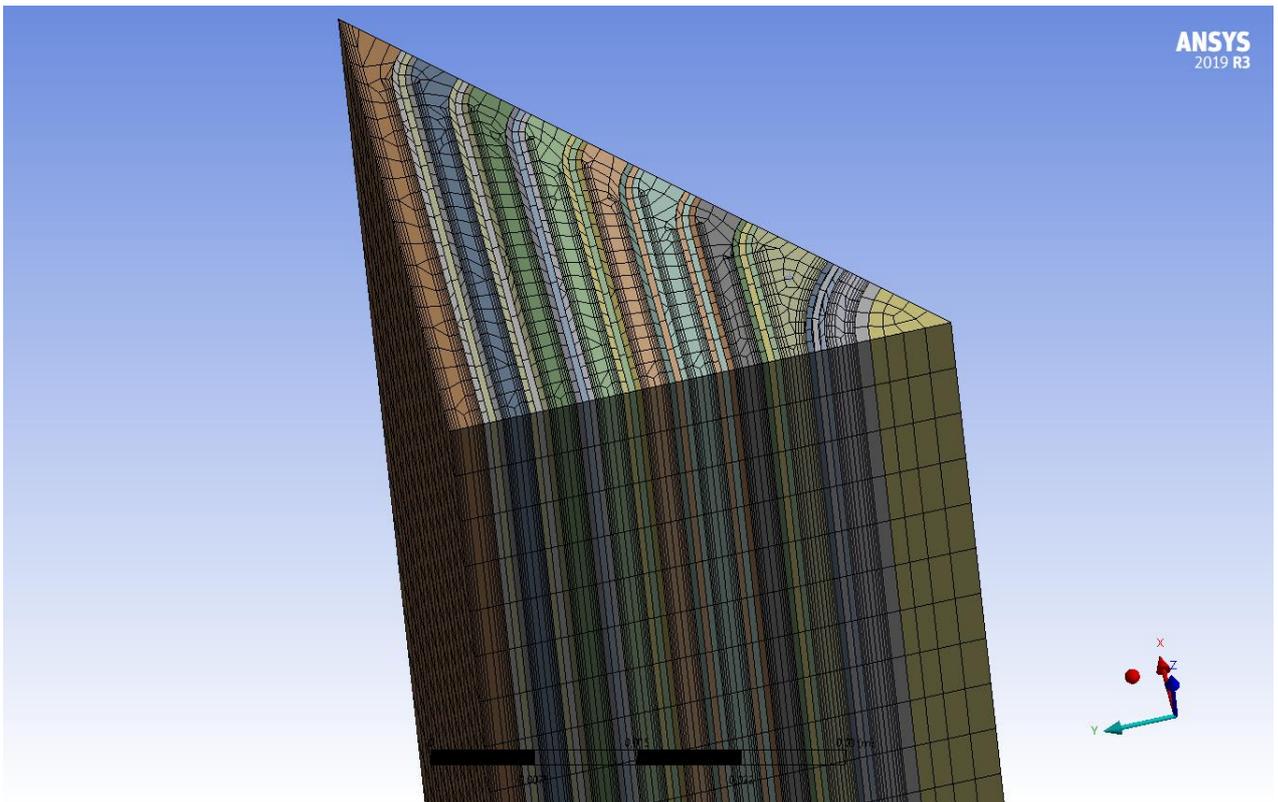


Figure 25 – Mesh for bodies below the upper part

2.6 Model setup

After generating mesh it's necessary to setup the problem. First of all, it's necessary to select manually all domains and boundary conditions. Top part of the model consists of two domains: fluid top and upper part of the fuel assembly. Upper part of the fuel assembly is just a solid domain without of any heat sources, in the model it has a role of the hydraulic obstacle. Fluid top domain consists of two fluid bodies: one body represents water flowing outside fuel assembly and the other one is water stream which flows throughout the assembly. Basing on the previous discussion of turbulence models SST model seems as the most preferable for the current model, because in the upper part of the fuel assembly there's a huge zone of the free stream, meanwhile in zones of clearance between fuel elements free stream zone are quite tiny and thus near wall area requires better modelling. Reference pressure for both fluid domains is set as 1 atmosphere.

Upper fluid domain contains two boundary conditions: symmetry and inlet. Symmetry is placed due to the symmetry of the fuel assembly. Inlet boundary condition was set in terms of relative pressure as 37 kPa and inlet temperature of coolant was set as 45 °C which is the maximum permissible value for this parameter.

For description of water flowing around fuel elements Fluid_fuel domain was setup. It contains symmetry condition and outlet boundary condition. To model pressure drop for water flowing through the fuel assembly relative pressure at the outlet from it was set to be 0.

Cladding part was modelled by the domain with the same name. This domain doesn't contain boundary conditions. As it was mentioned before cladding is made of aluminium material, so that due to the absence of free access to the properties of this material it seems to be that the best approximation to solve this problem will be choice of aluminium.

Fuel part of the fuel elements was modelled by the domain with the same name and it contains subdomains for each fuel part. Each fuel part produces different values of heat. Values of power have been obtained by modelling of the active zone of the IRT-T reactor in the verified model of it by means MCU-TPU5 program. Values of the power produced in each fuel element are presented in table 12. Material for each fuel element was set to be steel. This was chosen due to the same problem as it was for cladding – absence of data for fuel material. Steel seems to be the best approximation for fuel material due to the fact that iron is the closest element in the periodic table among available materials.

Table 12 – Heat production power for each fuel element

| Fuel element | Power, W |
|--------------|----------|
| 1 | 38667.2 |
| 2 | 35754.3 |
| 3 | 34072.3 |
| 4 | 33249.5 |
| 5 | 32711.9 |

Continuation of table 12

| Fuel element | Power, W |
|--------------|----------|
| 6 | 33247.4 |
| 7 | 34535.7 |
| 8 | 37214.1 |

After instantiation of the problem it's possible to launch solver and obtain solution results.

2.7 Discussion of the results

2.7.1 Results for the upper part of the assembly

As it can be seen from figure figure 26 solid body in the upper part of the fuel assembly has almost isothermal temperature distribution. This is easily explained by the absence of heat sources for this part of the fuel assembly. Only slight deviations from inlet temperature of the coolant are observed in the area near to the contact surface between fuel elements and the upper part of the assembly.

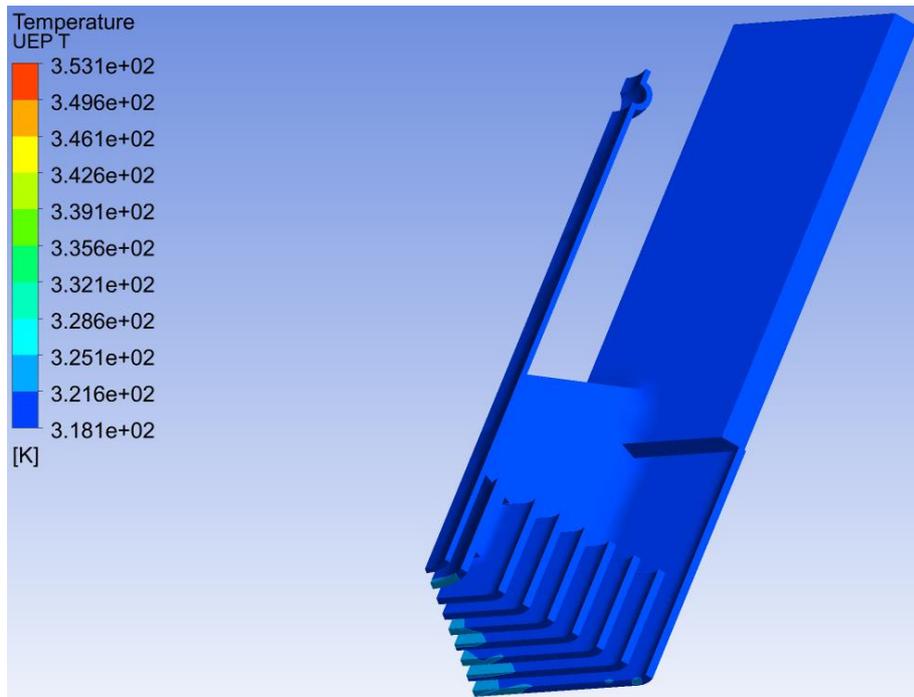


Figure 26 – Temperature distribution in the upper part

Pattern of the initial temperature distribution in water (figure 27) which flows along cladding of the fuel elements slowly changes and at the outlet from fuel assembly temperature distribution achieves pattern which is depicted on figure 28. As it can be seen on both figures, water around external fuel element is heated more than in any other places, because it's the most energetically strained fuel element. In all areas of water flowing through fuel assembly temperature of water achieves value of temperature which doesn't exceed permissible value of temperature. At the outlet of fuel assembly, the biggest value of temperature is 67 °C.

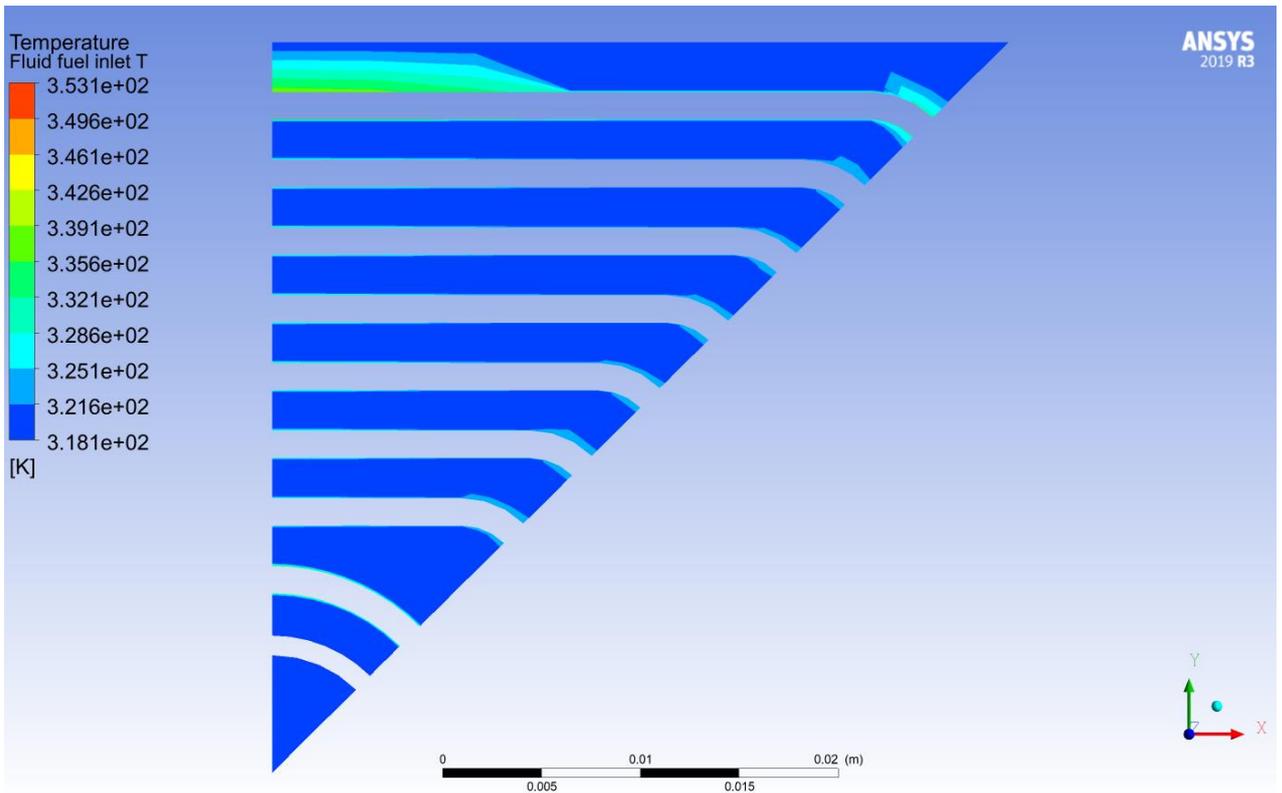


Figure 27 – Inlet into the fuel part temperature distribution

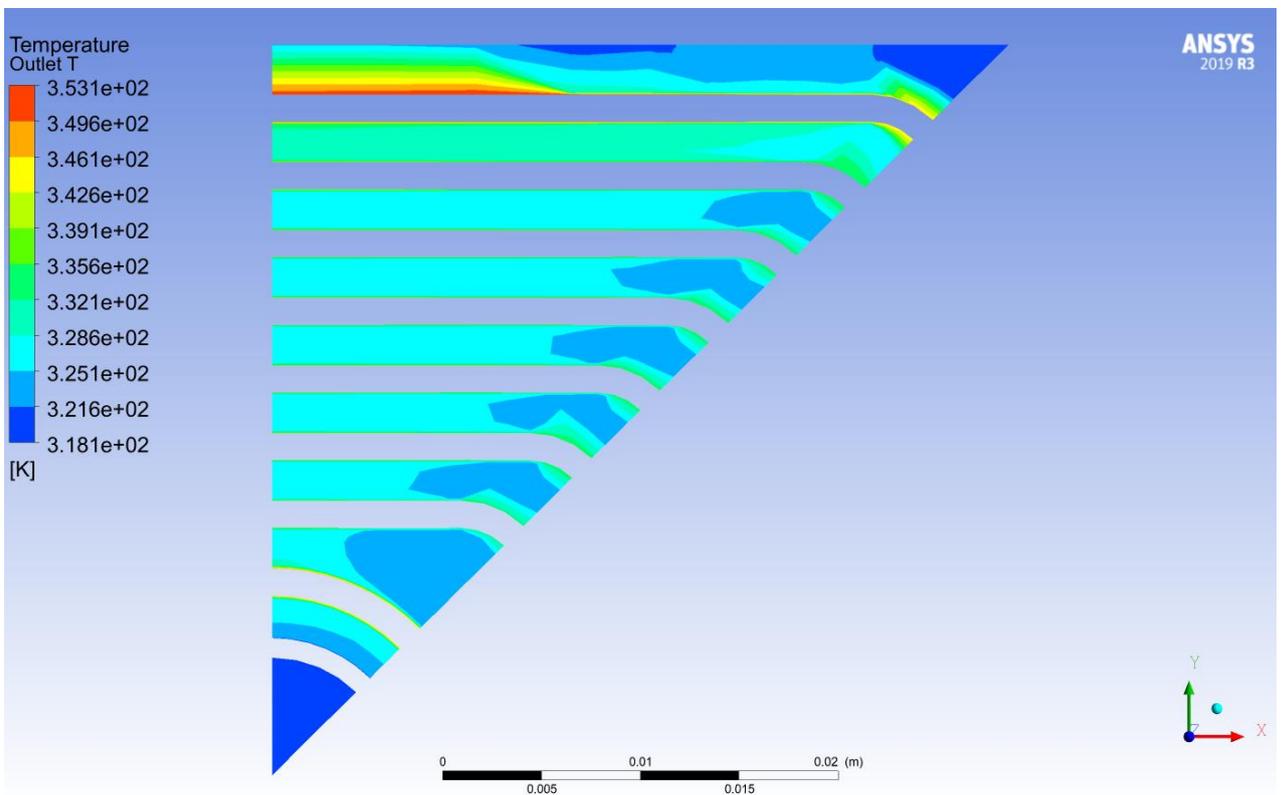


Figure 28 – Temperature distribution at the outlet from fuel assembly

Outer fuel element is the most power strained so that it's the most heated up body in the model. Maximal temperature on the surface of the cladding of the outer element at the outlet from heated zone is 79 °C. Also the maximum value of temperature is in the fuel part of the outer fuel element, its value is 82 °C. In this fuel element the highest value of thermal flux density is achieved: 667 kW/m². This value is less than maximum permissible value of 800 kW/m².

Obtained values of temperature for water aren't beyond the maximum permissible values: the highest value of temperature in the water is 67 °C, at this temperature surface boiling is impossible. The same can be concluded for fuel elements values of heat flux, temperature on the surface fuel rod and fuel temperature don't exceed permissible values.

Analysis of the obtained data

All obtained results show that in the condition of nominal exploitation of IRT-T reactor values characterizing thermal-hydraulic performance of the IRT-3M fuel assembly are satisfying all safety requirements. Results are provided in table 13.

Table 13 – Comparison of the results

| Parameter | Obtained maximal value | TGRK | Upper limit | Difference, % |
|---|------------------------|------|-------------|---------------|
| Heat flux density from surface of the fuel element, kW/m ² | 667 | 728 | 800 | 8.38 |
| Temperature on the surface of fuel element, °C | 79 | 81 | 100 | 2.47 |
| Temperature of water, °C | 67 | 65 | 115 | 2.99 |

Data mentioned in the table 13 shows that results obtained in this only diverge from modelling conducted in [20]. The margin of divergence doesn't exceed 10%.

3 Financial management, resource efficiency and resource conservation

Aim of this section is discussion of competitiveness and resource effectiveness of the current work. Competitiveness is discussed by means of SWOT analysis. SWOT analysis allows to identify strengths, weaknesses, opportunities and threats which related to the project. In its turn identification of mentioned before characteristics of project allows to find necessary solutions for problems which may arise during the work on master thesis.

Also this works contains detailed discussion of the necessary financing of the current work. This financing requires funding of the salaries for the staff which is included in the work on master thesis and necessary equipment. The calculation of the resource efficiency indicator makes it possible to make a final assessment of the technical decision on individual criteria and in total.

3.1 Competitiveness analysis

To make the analysis of the competitiveness, there will be used an evaluation map, which is shown in table 14. The developing project and its competitor are evaluated for each criterion on a five-point scale, where 1 – the weakest position, and 5 – the strongest. Summary, the weights of criteria should equal 3.

Analysis of the competitiveness of technical solutions could be calculated as follows:

$$K = \sum B_i \cdot S_i \quad (3.3.1)$$

where K – competitiveness of developing project or competitor;

B_i – weight of criteria i (in unit fraction);

S_i – a score of criteria i .

There were chosen five criteria to evaluate rival methods. The most important ones were chosen the computational speed and results in accuracy. Computational speed cuts the time costs and results accuracy mitigates the probability of error.

Besides, there was marked out criteria of adaptation, because it is important not only use the box solution but also to create something based on the solution.

Criteria of interface and functionality were marked out less important. Interface criteria show the convenience of interaction between end-user and model. Functionality shows the relative amount of functions, which model can do.

In the beginning of the work on master thesis after setting of mathematical task question of choice of solver aroused. Currently there are two leading solutions in the field of mathematical modeling for engineering tasks, namely Ansys and Simulink. The main advantage of Ansys products is that they were initially produced for the problems of mathematical modelling of thermalhydraulics in contrast with Simulink which has more generally oriented solving approach for tasks of different fields of computational modelling.

Table 14 – A map for evaluation of the competitiveness

| Criteria | | Criteria weight | Score | | Competitiveness | |
|----------|-------------------|-----------------|----------------|-------|-----------------|-------|
| | | | Simulink model | Ansys | Simulink model | Ansys |
| 1 | Results accuracy | 0.3 | 4 | 4 | 3.2 | 3.2 |
| 2 | Functionality | 0.1 | 5 | 4 | 0.5 | 0.4 |
| 3 | Interface | 0.1 | 3 | 4 | 0.3 | 0.4 |
| 4 | Adaptation | 0.2 | 4 | 5 | 0.7 | 0.8 |
| 5 | Computation speed | 0.3 | 3 | 4 | 0.9 | 3.2 |
| | | 1 | 19 | 21 | 3.6 | 4 |

Table 14 shows that basing on the criteria mentioned in that table Ansys product is more preferable in comparison with Simulink modelling.

3.2 SWOT-analysis

The goal of SWOT analysis is to determine all the strengths and weaknesses of the project, which are considered as inner factors. Moreover, SWOT considers outer factors, which are opportunities and threats. Table 15 shows the interactive

matrix of the project, which contains the correlation between strengths and opportunities, which allows describing prospects of the project.

Therefore, by completing the SWOT analysis it could be summarized, that the current advantages of the project are dominating the above disadvantages.

Table 15 – Interactive matrix of the project

| | | |
|---|---|---|
| | <p>Strengths: S3. Power-up of reactor installations S3. Absence of necessity of drastic changes of reactors' internals S3. Absence of necessity to use external power resources</p> | <p>Weaknesses: W3. Lower values of power-up in comparison with active methods W3. Absence experimental tests W3. High demand of computational resources</p> |
| <p>Opportunities: O3. Increased rate of production of radio-products O3. Simplified implementation of technology on reactor site O3. Possibility of conduction of new research activities</p> | <p>Strategy which based on strengths and opportunities: 3. Power-up leads to increase in rate of production of radio-products 3. Power-up leads to increased levels of neutron fluxes of all energies, hence to possibility of new experiments 3. Growth of cost recovery of the reactor installation</p> | <p>Strategy which based on weaknesses and opportunities: Simplified implementation of technology may cover cost of losses from lower gains in thermal power</p> |
| <p>Threats: T3. Possibility of shutdown of the reactor which use fuel elements of interest T3. Absence of necessity to conduct power-up T3. High bureaucratic barriers</p> | <p>Strategy which based on strengths and threats: 3. Increased potential of reactor installation might lead to increase in its' lifetime 3. Simplicity and high reliability due to absence of external power sources may help to overcome bureaucratic barriers in comparison with methods with higher power-up</p> | <p>Strategy based on weaknesses and threats: Absence of experimental tests and high bureaucratic barriers on their way are the main drawbacks of the current investigation</p> |

3.3 Project initiation

As concerned parties, there are organizations or individuals who are actively taking part in the project or which interests can be considered both positively or

negatively in duration of the project or after its finish. These parties could be customers, sponsors, public sphere and etc. Information about concerning parties is represented in table 16.

Table 16 – Stakeholders of the project

| Stakeholder | Stakeholder's expectations |
|--|---|
| Division of nuclear fuel cycle, ESNT TPU | A model clearly simulating thermal-hydraulic processes in fuel assembly with modified heat-exchanging surface |

Table 17 provides necessary information on the hierarchy of project goals and criteria for achieving these goals.

Table 17 – Goals and results of the project

| | |
|---|--|
| Purpose of project: | Development of a computer-aided model for assessment of thermohydraulic performance of IRT-3M fuel assembly with modified surface |
| Expected results of the project: | Thermal hydraulic models of fuel assemblies with modified heat-exchanging surfaces |
| Criteria for acceptance of the project result: | Absence of errors during the simulation |
| Requirements to project results: | Requirement: |
| | Model produces results consistent with physical reality. Results temperature distributions in all parts which were modelled for fuel assembly under conditions of powered up performance |
| | Consistence with experimental data |

At the current stage it is important to decide who will be in the workgroup of this project, to define roles for each participant and to assign the functions for each participant. Besides, there should be considered working hours. This information is represented in table 18.

Table 18 – Project workgroup

| № | First name, Second name, primary employment, position | Project role | Functions | Working hours, h |
|----------|--|---------------------|-------------------------------------|-----------------------------|
| 1 | Butov V.G., professor of the division of nuclear fuel cycle, ESNT | Scientific advisor | Consulting | 114 |
| 2 | Nemykin N.V., student | Engineer | Making the computer- aided model | 402 |
| Total | | | | 516 |

3.4 Project budget

Project constraints are the factors, which are limiting the degree of freedom for project team members and serving as boundaries of the project.

Table 19 – Project constraints

| Factor | Constraints/Admissions |
|---|---|
| 3.3. Project budget, roubles | 87479 |
| 3.3.3. Funding source | National Research Tomsk Polytechnic University |
| 3.3. Project lifetime: | 03.03.2020-09.05.2020 |
| 3.3.3. The certified date for the plan of project management | 05.03.2020 |
| 3.3.3. Project deadline | 25.05.2020 |

3.5 Timing schedule of the project

As part of the planning of a research project, it is necessary to build a timetable and a calendar schedule for the project. The timetable is shown in table 20. Scientific advisor and an engineer are the main contributors to the report.

Table 20 – Timetable of the project

| № | Milestone | Duration, days | Start date | Finish date | Performer |
|----|--|----------------|------------|-------------|--------------------------------|
| 1 | Development of research task | 6 | 03.03.2020 | 07.03.2020 | Scientific advisor Engineer |
| 2 | Selecting and studying the related literature | 16 | 08.03.2020 | 27.03.2020 | Engineer |
| 3 | Work scheduling | 3 | 28.03.2020 | 33.03.2020 | Engineer |
| 4 | Research task writing and accepting | 1 | 03.04.2020 | 03.04.2020 | Scientific advisor Engineer |
| 5 | Familiarization with ANSYS CFX package | 5 | 03.04.2020 | 07.04.2019 | Engineer |
| 6 | Development of a geometrical model of fuel assembly with smooth heat-exchanging surface | 5 | 03.04.2020 | 07.04.2020 | Engineer |
| 7 | Development of a geometrical model of fuel assembly with various heat-exchanging surface | 4 | 13.04.2020 | 17.04.2020 | Engineer |
| 8 | Development computational models of fuel assemblies in ANSYS CFX | 5 | 18.04.2020 | 23.04.2020 | Engineer |
| 9 | Intermediate inspection, conversation with scientific advisor | 1 | 24.04.2020 | 24.04.2020 | Scientific advisor Engineer |
| 10 | Detailed report writing | 5 | 25.04.2020 | 30.04.2020 | Scientific advisor Engineer |
| 11 | Inspection of detailed report on standard compliance | 2 | 03.05.2019 | 04.05.2019 | Scientific advisor |
| 12 | Preparations to the defense of the thesis | 28 | 04.05.2019 | 03.06.2019 | Engineer |

Calendar schedule of the project, implemented by Gantt chart is represented in table 21.

Table 21 – Gantt chart

| Stage | Content of work | T _c , days | Duration of works | | | | | | | | | | | |
|-------|---|-----------------------|-------------------------------|--------------------|---|---|-------|---|---|---|-----|---|---|--|
| | | | March | | | | April | | | | May | | | |
| 1 | Development of research task | 7 | █ | | | | | | | | | | | |
| 2 | Selection and studying the related literature | 19 | █ | █ | █ | █ | █ | | | | | | | |
| 3 | Work scheduling | 3 | | | | █ | | | | | | | | |
| 4 | Research task writing and accepting | 1 | | | | | █ | | | | | | | |
| 5 | Familiarization with ANSYS CFX package | 5 | | | | | █ | █ | | | | | | |
| 6 | Development of a single-group nuclear reactor kinetics model | 5 | | | | | | █ | █ | | | | | |
| 7 | Development of a six-group nuclear reactor kinetics model | 5 | | | | | | | █ | █ | | | | |
| 8 | Development of a six-group nuclear reactor kinetics model coupled with thermal hydraulics effects | 5 | | | | | | | | █ | █ | | | |
| 9 | Intermediate inspection, conversation with scientific advisor | 1 | | | | | | | | | █ | | | |
| 10 | Detailed report writing | 6 | | | | | | | | | | █ | | |
| 11 | Inspection of detailed report on standard compliance | 7 | | | | | | | | | | | █ | |
| 12 | Preparations to the defense of a thesis | 28 | | | | | | | | | | | █ | |
| | Total days | 92 | █ | Scientific advisor | | | | | | | | 7 | | |
| █ | | | Scientific advisor + Engineer | | | | | | | | 15 | | | |
| █ | | | Engineer | | | | | | | | 70 | | | |

3.6 Budget of scientific research

3.6.1 Material costs of scientific research

For current work, academic version Ansys software was used, which is free.

Besides, there was used a laptop with cost 30590 rubles, which is less than 40000 rubles, hence depreciation of hardware is not necessary

Material costs, required for this research are shown in table 22.

Table 22 – Material costs

| Name | Amount (S_{mat}), rub |
|------------------------|---------------------------|
| Office supplies | 1000 |
| Access to the Internet | 1050 |

Continuation of table 22

| Name | Amount (S_{mat}), rub |
|--------|---------------------------|
| Laptop | 30590 |
| Total: | 32640 |

3.6.2 Calculation of the base salary

Current calculation contains the calculation of salaries for the scientific advisor and student. Costs for salary are calculated based on workload and the current system of emoluments. Besides base salary contains 10% bonus, paid monthly from payroll.

Table 23 – Emolument calculation

| Contractor | Salary, rub |
|-------------------------------|-------------|
| Scientific advisor, professor | 21760 |
| Engineer | 17310 |

$$S_{sal} = S_{base} + S_{bon}, \quad (23)$$

where S_{base} – base salary;

S_{bon} – bonus to salary (10 % from S_{base}).

Base salary is calculated by the next formula:

$$S_{base} = S_d \cdot T_w, \quad (24)$$

where S_{base} – base salary;

T_r – duration of works, made by the scientific worker, w.days;

S_d – daily salary of a worker, rub.

Daily salary can be calculated by the next formula:

$$S_d = \frac{S_{em} \cdot M}{F_d}, \quad (25)$$

where S_{em} – monthly emolument of the worker, rub.;

M – the amount of months without vacations during the year (10,4 for six-days working week); $M = 13.2$ months, 6 day per week

F_d – current annual working hours for scientific workers, w. days.

Table 24 – Balance of working time

| Criteria for working time | Scientific advisor | Engineer |
|---|--------------------|----------|
| Calendar amount of days | 365 | 365 |
| Amount of non-work days: | 66 | 66 |
| weekend; | 52 | 52 |
| holidays. | 14 | 14 |
| Loss of working days, days: | 48 | 48 |
| vacation; | 48 | 48 |
| sick absence. | 0 | 0 |
| Current annual working hours F_d , days | 251 | 251 |

Monthly position salary is calculated as follows:

$$S_m = S_{em} \cdot k_r, \quad (26)$$

where S_{em} – monthly position salary, rub.;

k_p – regional salary coefficient (1,3 for Tomsk).

Base salary calculation for the scientific advisor and for an engineer is in t25.

Table 25 – Base salary calculation

| Performers | S_{em} , rub. | k_r | S_m , rub | S_d , rub. | T_w , w.days. | S_{base} , rub | S_{bon} , rub |
|-----------------------|--------------------|-------|-------------|--------------|-----------------|------------------|-----------------|
| Scientific advisor | 21760 | 3.3 | 28288 | 1263.25 | 22 | 27769.57 | 2776.96 |
| Engineer | 17310 | 3.3 | 22503 | 1004.12 | 85 | 85350.02 | 8535 |

The base salary for a scientific advisor from TPU is calculated based on industrial remuneration. In TPU this remuneration considers next content for salary:

- emolument, determined by the enterprise;
- incentive payments, determined by the head of departments for efficient work, the accomplishment of job duties and etc.;
- other payments;

- regional salary coefficient.

Additional salary equals to 10% from the base salary. According to calculations, the additional salary for an engineer is 3521 rubles and for scientific advisor, it is 1713 rubles.

3.6.3 Contributions in non-budget funds

This part of costs shows the necessary contribution according to laws of the Russian Federation about social assurance, pension fund and medical insurance from costs on salary.

Contributions are calculated as follows:

$$S_{soc} = k_{contr} \cdot (S_{base} + S_{bon}), \quad (27)$$

where k_{contr} – the coefficient for contributions in non-budget funds.

Besides, contributions in non-budget funds are not required for scholarships. At the moment of the 2020 year, the insurance fees are 30%, however, for education enterprises, there is a reduced rate equal to 27,1%.

Results of calculation for social funds are presented in table 25.

Table 26 – Contributions in non-budget funds

| | Scientific advisor | Engineer |
|---|--------------------|----------|
| Base salary, rub. | 27769.57 | 85350.02 |
| Additional base salary, rub. | 2776.96 | 8535 |
| Coefficient for non-budget contributions, % | 27.1 | |
| Total, rub. | 7525.56 | 23129.86 |

3.6.4 Overhead costs

Overhead costs are usually 30% from the sum of base salary and additional salary of workers, who are involved in the research project.

$$S_{overh} = k_{overh} \cdot (S_{base} + S_{bon}) = 37329.47 \text{ rub.} \quad (28)$$

Main works for research project were made on a laptop for three months. The output voltage of laptop equals 19V and output current is 4.74 A. Hence, the output power of the laptop is 90 W or 0.09 kW.

3.6.5 Other direct costs

Costs on electric energy are calculated as follows:

$$S_e = C_{el} \cdot P \cdot F_{hw}, \quad (29)$$

where C_{el} – energy rate (5,8 rub per 1 kW·h);

P – hardware power, kW;

F_{hw} – hardware time of use, h.

Therefore, costs for electric energy during the time of use of laptop:

$$S_e = 5.8 \cdot 0.09 \cdot 402 = 209.84 \text{ rub.} \quad (30)$$

3.6.6 Budgeting of project costs

Calculated costs for research work is a base for budgeting of project costs, which is a lower limit for scientific-technical production costs.

Table 27 – Budgeting of project costs

| Cost item | Amount, rub. | |
|--------------------------------------|--------------------|-----------|
| | Scientific advisor | Engineer |
| Main salary costs | 27769.57 | 85350.02 |
| Contributions in non-budgetary funds | 7525.56 | 23129.86 |
| Total costs | 35295.13 | 108479.86 |
| Overhead costs | 37329.47 | |
| Material costs | 32640 | |
| Other material costs | 208.84 | |
| Total | 213954.3 | |

3.7 Conclusions on financial management part

There was made a financial analysis of the development. During this analysis, there were carried out the budgeting of scientific project, SWOT analysis, investigated possible competitive solutions.

As a result, the current project is more competitive from the point of resource saving, because its competitiveness is 3.9 against 3.8 of competitor option. Besides, the budget of the project equals 87479 rubles and integrating efficiency indicator equals 4.5, which is 3.18 times higher than competitor option.

3.8 Evaluation of the comparative effectiveness of the project

Determination of efficiency is based on the calculation of the integral indicator of the effectiveness of scientific research. Its finding is associated with the definition of two weighted average values: financial efficiency and resource efficiency.

The integral indicator of the financial efficiency of a scientific study is obtained in the course of estimating the budget for the costs of three (or more) variants of the execution of a scientific study. For this, the largest integral indicator of the implementation of the technical problem is taken as the calculation base (as the denominator), with which the financial values for all the options are correlated.

The integral financial measure of development is defined as:

$$I_{\phi}^p = \frac{\Phi_{pi}}{\Phi_{\max}} \quad (31)$$

where I_{ϕ}^p – integral financial measure of development;

Φ_{pi} – the cost of the i-th version;

Φ_{\max} – the maximum cost of execution of a research project (including analogues).

The obtained value of the integral financial measure of development reflects the corresponding numerical increase in the budget of development costs in times (the value is greater than one), or the corresponding numerical reduction in the cost of development in times (the value is less than one, but greater than zero).

Since the development has one performance, then $I_{\phi}^p = 3$.

The integral indicator of the resource efficiency of the variants of the research object can be determined as follows:

$$I_m^a = \sum_{i=1}^n a_i b_i^a, I_m^p = \sum_{i=1}^n a_i b_i^p \quad (32)$$

where I_m – integral indicator of resource efficiency for the i-th version of the development;

a_i – the weighting factor of the i-th version of the development;

b_i^a, b_i^p – score rating of the i-th version of the development, is established by an expert on the selected rating scale;

n – number of comparison parameters.

The calculation of the integral indicator of resource efficiency is presented in table 28.

Table 28 – Evaluation of the performance of the project

| Criteria | Weight criterion | Points |
|--|------------------|--------|
| Necessary computational power | 0.15 | 2 |
| Value of the possible power-up | 0.13 | 3 |
| Simplicity of machining | 0.21 | 5 |
| Materials consumption | 0.08 | 3 |
| Reliability | 0.11 | 3 |
| Security | 0.08 | 3 |
| Economic criteria for performance evaluation | | |
| Price | 0.12 | 4 |
| Technology competitiveness | 0.12 | 5 |
| Total | 1 | 27 |

The integral indicator of the development efficiency $\left(I_{\text{финр}}^p \right)$ is determined on the basis of the integral indicator of resource efficiency and the integral financial indicator using the formula:

$$I_{\text{финр}}^p = \frac{I_m^p}{I_{\phi}^p}, I_{\text{финр}}^a = \frac{I_m^a}{I_{\phi}^a} \quad (33)$$

Comparison of the integral indicator of the current project efficiency and analogues will determine the comparative efficiency. Comparative effectiveness of the project:

$$\mathcal{E}_{cp} = \frac{I_{\text{финр}}^p}{I_{\text{финр}}^a} \quad (34)$$

Thus, the effectiveness of the development is presented in table 29.

Table 29 – Efficiency of development

| № | Indicators | Points |
|---|--|--------|
| 1 | Integral financial measure of development | 1 |
| 2 | Integral indicator of resource efficiency of development | 5.79 |
| 3 | Integral indicator of the development efficiency | 5.79 |

Comparison of the values of integral performance indicators allows us to understand and choose a more effective solution to the technical problem from the standpoint of financial and resource efficiency.

Conclusion

During investigation in this chapter it was determined that almost all articles of spending require the same amount of financing. In contrast with all other articles

of spending labor costs stand out. Labor costs include in itself salaries for participants of the project. The number of work performers is two: student and supervisor from the school.

Also this chapter represents detailed calculations of all costs which relate to the current work and time which is necessary to spend to conduct the research. The planned cost of work is 213954.3 rubles, the pivotal component of which is the wages of employees.

4 Social responsibility

4.1 Introduction

The main aim of nuclear research reactors is production of neutron fluxes of huge value. Huge gain in value of neutron flux in the whole energy spectrum can be achieved via increase in thermal power of reactor. However, growth of thermal power leads to amplified heat load on reactor core. This load is concentrated in fuel rods. Because of non-allowability of exceedance maximum permissible value characterizing heat duty, it's necessary in the case of increase in thermal power to take additional measures which can provide intensified heat removal from fuel rods.

One of such measure is implementation of intensification of heat exchange through implementation of passive heat removal methods. To analyze possibility of implementation of such technology in the reactor's core modelling of the fuel assembly was conducted in this work. The calculations were performed with the help of the Ansys software and the results were analyzed. Results of these calculations can be directly used for power-up of the IRT-T reactor.

The work was done in the Research Institute of Applied Mathematics and Mechanics, Tomsk State University, Tomsk city.

4.2 Legal and organizational items in providing safety

Nowadays one of the main ways to radical improvement of all prophylactic work referred to reduce Total Incidents Rate and occupational morbidity is the widespread implementation of an integrated Occupational Safety and Health management system. That means combining isolated activities into a single system of targeted actions at all levels and stages of the production process.

Occupational safety is a system of legislative, socio-economic, organizational, technological, hygienic and therapeutic and prophylactic measures and tools that ensure the safety, preservation of health and human performance in the work process[21].

According to the Labor Code of the Russian Federation, every employee has the right:

- to have a workplace that meets Occupational safety requirements;
- to have a compulsory social insurance against accidents at manufacturing and occupational diseases;
- to receive reliable information from the employer, relevant government bodies and public organizations on conditions and Occupational safety at the workplace, about the existing risk of damage to health, as well as measures to protect against harmful and (or) hazardous factors;
- to refuse carrying out work in case of danger to his life and health due to violation of Occupational safety requirements;
- be provided with personal and collective protective equipment in compliance with Occupational safety requirements at the expense of the employer;
- for training in safe work methods and techniques at the expense of the employer;
- for personal participation or participation through their representatives in consideration of issues related to ensuring safe working conditions in his workplace, and in the investigation of the accident with him at work or occupational disease;
- for extraordinary medical examination in accordance with medical recommendations with preservation of his place of work (position) and secondary earnings during the passage of the specified medical examination;
- for warranties and compensation established in accordance with this Code, collective agreement, agreement, local regulatory an act, an employment contract, if he is engaged in work with harmful and (or) hazardous working conditions.

The labor code of the Russian Federation states that normal working hours may not exceed 40 hours per week. The employer must keep track of the time worked by each employee. Rules for labor protection and safety measures are introduced in order to prevent accidents, ensure safe working conditions for workers and are mandatory for workers, managers, engineers and technicians.

4.3 Basic ergonomic requirements for the correct location and arrangement of researcher's workplace

The workplace when working with a PC should be at least 6 square meters. The legroom should correspond to the following parameters: the legroom height is at least 600 mm, the seat distance to the lower edge of the working surface is at least 150 mm, and the seat height is 420 mm. It is worth noting that the height of the table should depend on the growth of the operator.

The following requirements are also provided for the organization of the workplace of the PC user: The design of the working chair should ensure the maintenance of a rational working posture while working on the PC and allow the posture to be changed in order to reduce the static tension of the neck and shoulder muscles and back to prevent the development of fatigue.

The type of working chair should be selected taking into account the growth of the user, the nature and duration of work with the PC. The working chair should be lifting and swivel, adjustable in height and angle of inclination of the seat and back, as well as the distance of the back from the front edge of the seat, while the adjustment of each parameter should be independent, easy to carry out and have a secure fit.

4.4 Occupational safety

A dangerous factor or industrial hazard is a factor whose impact under certain conditions leads to trauma or other sudden, severe deterioration of health of the worker[21].

A harmful factor or industrial health hazard is a factor, the effect of which on a worker under certain conditions leads to a disease or a decrease in working capacity.

4.4.1 Analysis of harmful and dangerous factors that can create object of investigation

The object of investigation is “Thermal-hydraulic calculation of the IRT-3M type fuel assembly in the IRT-T reactor with various energy conduction surfaces” by simulation on the PC. Therefore, object of investigation itself cannot cause harmful and dangerous factors.

4.4.2. Analysis of harmful and dangerous factors that can arise at workplace during investigation

The working conditions in the workplace are characterized by the presence of hazardous and harmful factors, which are classified by groups of elements: physical, chemical, biological, psychophysiological. The main elements of the production process that form dangerous and harmful factors are presented in the table 29.

Table 30 – Possible hazardous and harmful factors

| Factors (GOST 12.0.003-2015) | Work stages | | | Legal documents |
|---|-------------|-------------|--------------|--|
| | Development | Manufacture | Exploitation | |
| 1. Deviation of microclimate indicators | + | + | + | Sanitary rules 2.2.2 / 2.4.1340–03. Sanitary and epidemiological rules and regulations "Hygienic requirements for personal |
| 2. Excessive noise | | + | + | |
| 3. Increased level of electromagnetic radiation | + | + | + | |

| | | | |
|--|--|--|--|
| | | | <p>electronic computers and work organization."</p> <p>Sanitary rules 2.2.1 / 2.1.1.1278–03. Hygienic requirements for natural, artificial and combined lighting of residential and public buildings.</p> <p>Sanitary rules 2.2.4 / 2.1.8.562–96. Noise at workplaces, in premises of residential, public buildings and in the construction area.</p> <p>Sanitary rules 2.2.4.548–96. Hygienic requirements for the microclimate of industrial premises.</p> |
|--|--|--|--|

Continuation of table 30

| Factors (GOST 12.0.003-2015) | Work stages | | | Legal documents |
|---|-------------|-------------|--------------|---|
| | Development | Manufacture | Exploitation | |
| 4. Insufficient illumination of the working area | | + | + | |
| 5. Abnormally high voltage value in the circuit, the closure which may occur through the human body | + | + | + | Sanitary rules GOST 12.1.038-82 SSBT. Electrical safety. Maximum permissible levels of touch voltages and currents. |

The following factors effect on person working on a computer:

- physical:
 - temperature and humidity;
 - noise;
 - static electricity;
 - electromagnetic field of low purity;
 - illumination;
 - presence of radiation;
- psychophysiological:
 - psychophysiological dangerous and harmful factors are divided into:
 - physical overload (static, dynamic);
 - mental stress (mental overstrain, monotony of work, emotional overload).

Deviation of microclimate indicators

The air of the working area (microclimate) is determined by the following parameters: temperature, relative humidity, air speed. The optimum and permissible values of the microclimate characteristics are established in accordance with [22] and are given in table 31.

Table 31 – Optimal and permissible parameters of the microclimate

| Period of the year | Temperature, °C | Relative humidity, % | Speed of air movement, m/s |
|------------------------------|-----------------|----------------------|----------------------------|
| Cold and changing of seasons | 23-25 | 40-60 | 0.1 |
| Warm | 23-25 | 40 | 0.1 |

Excessive noise

Noise and vibration worsen working conditions, have a harmful effect on the human body, namely, the organs of hearing and the whole body through the central nervous system. It result in weakened attention, deteriorated memory, decreased response, and increased number of errors in work. Noise can be generated by operating equipment, air conditioning units, daylight illuminating devices, as well as spread from the outside. When working on a PC, the noise level in the workplace should not exceed 50 dB.

Increased level of electromagnetic radiation

The screen and system blocks produce electromagnetic radiation. Its main part comes from the system unit and the video cable. According to [22], the intensity of the electromagnetic field at a distance of 50 cm around the screen along the electrical component should be no more than:

- in the frequency range 5 Hz - 2 kHz - 25 V/m;
- in the frequency range 2 kHz - 400 kHz - 2.5 V/m.

The magnetic flux density should be no more than:

- in the frequency range 5 Hz - 2 kHz - 250 nT;
- in the frequency range 2 kHz - 400 kHz - 25 nT.

Abnormally high voltage value in the circuit

Depending on the conditions in the room, the risk of electric shock to a person increases or decreases. Do not operate the electronic device in conditions of high humidity (relative air humidity exceeds 75 % for a long time), high temperature (more than 35 °C), the presence of conductive dust, conductive floors and the possibility of simultaneous contact with metal components connected to the ground and the metal casing of electrical equipment. The operator works with electrical devices: a computer (display, system unit, etc.) and peripheral devices. There is a risk of electric shock in the following cases:

- with direct contact with current-carrying parts during computer repair;
- when touched by non-live parts that are under voltage (in case of violation of insulation of current-carrying parts of the computer);
- when touched with the floor, walls that are under voltage;
- short-circuited in high-voltage units: power supply and display unit.

Table 32 – Upper limits for values of contact current and voltage

| | Voltage, V | Current, mA |
|-------------------|------------|-------------|
| Alternate, 50 Hz | 2 | 0.3 |
| Alternate, 400 Hz | 3 | 0.4 |
| Direct | 8 | 1.0 |

Insufficient illumination of the working area

Light sources can be both natural and artificial. The natural source of the light in the room is the sun, artificial light are lamps. With long work in low illumination conditions and in violation of other parameters of the illumination, visual perception decreases, myopia, eye disease develops, and headaches appear.

According to the standard, the illumination on the table surface in the area of the working document should be 300-500 lux. Lighting should not create glare on the surface of the monitor. Illumination of the monitor surface should not be more than 300 lux.

The brightness of the lamps of common light in the area with radiation angles from 50 to 90° should be no more than 200 cd/m, the protective angle of the lamps should be at least 40°. The safety factor for lamps of common light should be assumed to be 1.4. The ripple coefficient should not exceed 5 %.

4.4.3 Justification of measures to reduce the levels of exposure to hazardous and harmful factors on the researcher

Deviation of microclimate indicators

The measures for improving the air environment in the production room include: the correct organization of ventilation and air conditioning, heating of room. Ventilation can be realized naturally and mechanically. In the room, the following volumes of outside air must be delivered:

- at least 30 m³ per hour per person for the volume of the room up to 20 m³ per person;
- natural ventilation is allowed for the volume of the room more than 40 m³ per person and if there is no emission of harmful substances.

The heating system must provide sufficient, constant and uniform heating of the air. Water heating should be used in rooms with increased requirements for clean air.

The parameters of the microclimate in the laboratory regulated by the central heating system, have the following values: humidity 40 %, air speed 0.1 m/s, summer temperature 20-25 °C, in winter 13-15 °C. Natural ventilation is provided in the laboratory. Air enters and leaves through the cracks, windows, doors. The main disadvantage of such ventilation is that the fresh air enters the room without preliminary cleaning and heating.

Excessive noise

In research audiences, there are various kinds of noises that are generated by both internal and external noise sources. The internal sources of noise are working

equipment, personal computer, printer, ventilation system, as well as computer equipment of other engineers in the audience. If the maximum permissible conditions are exceeded, it is sufficient to use sound-absorbing materials in the room (sound-absorbing wall and ceiling cladding, window curtains). To reduce the noise penetrating outside the premises, install seals around the perimeter of the doors and windows.

Increased level of electromagnetic radiation

There are the following ways to protect against EMF:

- increase the distance from the source (the screen should be at least 50 cm from the user);
- the use of pre-screen filters, special screens and other personal protective equipment.

When working with a computer, the ionizing radiation source is a display. Under the influence of ionizing radiation in the body, there may be a violation of normal blood coagulability, an increase in the fragility of blood vessels, a decrease in immunity, etc. The dose of irradiation at a distance of 20 cm to the display is 50 $\mu\text{rem/hr}$. According to the norms [22], the design of the computer should provide the power of the exposure dose of x-rays at any point at a distance of 0.05 m from the screen no more than 100 $\mu\text{R/h}$.

Fatigue of the organs of vision can be associated with both insufficient illumination and excessive illumination, as well as with the wrong direction of light.

Abnormally high voltage value in the circuit

Measures to ensure the electrical safety of electrical installations:

- disconnection of voltage from live parts, on which or near to which work will be carried out, and taking measures to ensure the impossibility of applying voltage to the workplace;
- posting of posters indicating the place of work;
- electrical grounding of the housings of all installations through a neutral wire;

- coating of metal surfaces of tools with reliable insulation;
- inaccessibility of current-carrying parts of equipment (the conclusion in the case of electroporating elements, the conclusion in the body of current-carrying parts) [23].

Insufficient illumination of the working area

Desktops should be placed in such a way that the monitors are oriented sideways to the light openings, so that natural light falls mainly on the left.

Also, as a means of protection to minimize the impact of the factor, local lighting should be installed due to insufficient lighting, window openings should be equipped with adjustable devices such as blinds, curtains, external visors, etc.

4.5 Ecological safety

4.4.1 Analysis of the impact of the research object on the environment

Most nuclear power plants release gaseous and liquid radiological effluents into the environment, which must be monitored. Civilians living within 80 km of a nuclear power plant typically receive about 0.1 μSv per year.

All reactors are required to have a containment building in according to international requirements. The walls of containment buildings are several feet thick and made of concrete and therefore can stop the release of any radiation emitted by the reactor into the environment

Large volumes of water are used during the process of nuclear power generation. The uranium fuel inside reactors undergoes induced nuclear fission which releases great amounts of energy that is used to heat water. The water turns into steam and rotates a turbine, creating electricity. Nuclear plants are built near bodies of water.

All possible impact of nuclear power plant on environment is greatly reduced in operating regime by many safety precautions means. The most danger of nuclear energy come because of different sorts of disaster.

4.4.2 Analysis of the environmental impact of the research process

Process of investigation itself in the thesis do not have essential effect on environment. One of hazardous waste is fluorescent lamps. Mercury in fluorescent lamps is a hazardous substance and its improper disposal greatly poisons the environment.

Outdated devices goes to an enterprise that has the right to process wastes. It is possible to isolate precious metals with a purity in the range of 99.95-99.99% from computer components. A closed production cycle consists of the following stages: primary sorting of equipment; the allocation of precious, ferrous and non-ferrous metals and other materials; melting; refining and processing of metals. Thus, there is an effective disposal of computer devices.

4.4.3 Justification of environmental protection measures

Pollution reduction is possible due to the improvement of devices that produces electricity, the use of more economical and efficient technologies, the use of new methods for generating electricity and the introduction of modern methods and methods for cleaning and neutralizing industrial waste. In addition, this problem should be solved by efficient and economical use of electricity by consumers themselves. This is the use of more economical devices, as well as efficient regimes of these devices. This also includes compliance with production discipline in the framework of the proper use of electricity.

Simple conclusion is that it is necessary to strive to reduce energy consumption, to develop and implement systems with low energy consumption. In modern computers, modes with reduced power consumption during long-term idle are widely used.

4.6 Safety in emergency

4.6.1 Analysis of probable emergencies that may occur at the workplace during research

The fire is the most probable emergency in our life. Possible causes of fire:

- malfunction of current-carrying parts of installations;
- work with open electrical equipment;
- short circuits in the power supply;
- non-compliance with fire safety regulations;
- presence of combustible components: documents, doors, tables, cable insulation, etc.

Activities on fire prevention are divided into: organizational, technical, operational and regime.

4.6.2 Substantiation of measures for the prevention of emergencies and the development of procedures in case of emergencies

Organizational measures provide for correct operation of equipment, proper maintenance of buildings and territories, fire instruction for workers and employees, training of production personnel for fire safety rules, issuing instructions, posters, and the existence of an evacuation plan.

The technical measures include compliance with fire regulations, norms for the design of buildings, the installation of electrical wires and equipment, heating, ventilation, lighting, the correct placement of equipment.

The regime measures include the establishment of rules for the organization of work, and compliance with fire-fighting measures. To prevent fire from short circuits, overloads, etc., the following fire safety rules must be observed:

- elimination of the formation of a flammable environment (sealing equipment, control of the air, working and emergency ventilation);

- use in the construction and decoration of buildings of non-combustible or difficultly combustible materials;
- the correct operation of the equipment (proper inclusion of equipment in the electrical supply network, monitoring of heating equipment);
- correct maintenance of buildings and territories (exclusion of the source of ignition - prevention of spontaneous combustion of substances, restriction of fireworks);
- training of production personnel in fire safety rules;
- the publication of instructions, posters, the existence of an evacuation plan;
- compliance with fire regulations, norms in the design of buildings, in the organization of electrical wires and equipment, heating, ventilation, lighting;
- the correct placement of equipment;
- well-time preventive inspection, repair and testing of equipment.

In the case of an emergency, it is necessary to:

- inform the management (duty officer);
- call the Emergency Service or the Ministry of Emergency Situations – tel. 112;
- take measures to eliminate the accident in accordance with the instructions.

4.7 Conclusions

In this section about social responsibility the hazardous and harmful factors were revealed. All necessary safety measures and precaution to minimize probability of accidents and traumas during investigation are given.

Possible negative effect on environment were given in compact form describing main ecological problem of using nuclear energy.

It could be stated that with respect to all regulations and standards, investigation itself and object of investigation do not pose special risks to personnel, other equipment and environment.

Conclusion

Nuclear research reactor of Tomsk Polytechnic University was observed in the current work. The main technical characteristics of the reactor's cooling system of fuel assemblies were observed. Also this work contains review of the passive techniques for intensification of the heat-exchange in channels of the nuclear reactors. The work provides data about physical mechanisms lying in intensification of heat exchange process by usage of turbulizers. Basing on the observation of multiple scientific works dedicated to intensification of heat exchange via implementation of turbulizers, number of recommendations for construction of modified heat exchanging surfaces of fuel assemblies IRT-3M type were made.

Further work was dedicated to the creation of computational models. First of all, detailed geometrical model of IRT-3M fuel assembly was made. Then basing on the instructions obtained from literature review geometrical models of the assembly with modified heat-exchanging surfaces were made. This part of work has resulted into 3 geometrical models of fuel assembly: with smooth heat-exchanging surface, ribbed surface and surface wrapped in wire coil.

Initially it was planned that the next stage of the work should be resulted into modelling of all three geometries. However, due to the lock-down access to the commercial version of Ansys was not available, so that it was only possible to use only student's license. Student license puts restrictions on the permissible number of surfaces in the model, thus it was possible to conduct modelling of only simplified model of IRT-3M fuel assembly.

Further results were obtained during modelling:

- Maximal temperature of water at the outlet of fuel elements is 67 °C;
- maximal value of the heat flux from fuel elements to the coolant is 667 kW/m²;
- Maximal temperature on the surface of cladding is 79 °C.

Thus, it can be concluded that values characterizing thermal-hydraulic performance of IRT-3M fuel assembly in the core of Tomsk Polytechnic University's

reactor are far below maximal permissible values. So that further power-up is still possible without implementation of any additional options.

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