Evaluated Experimental Database on Critical Heat Flux in WWER FA Models

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Abstract

The paper presents the description of the evaluated experimental database on critical heat flux in WWER FA models of new designs. This database was developed on the basis of the experimental data obtained in the years of 2009-2012.

In the course of its development, the database was reviewed in terms of completeness of the information about the experiments and its compliance with the requirements of Rostekhnadzor regulatory documents. The description of the experimental FA model characteristics and experimental conditions was specified. Besides, the experimental data were statistically processed with the aim to reject incorrect ones and the sets of experimental data on critical heat fluxes (CHF) were compared for different FA models.

As a result, for the first time, the evaluated database on CHF in FA models of new designs was developed, that was complemented with analysis functions, and its main purpose is to be used in the process of development, verification and upgrading of calculation techniques.

The developed database incorporates the data of 4183 experimental conditions obtained in 53 WWER FA models of various designs.

Keywords: WWER reactor, fuel assembly, CHF, evaluated experimental data, database, statistical analysis.

1. Introduction

The planned WWER NPP power ascension provides for the need in reactor core heat transfer enhancement with the aim of FA cooling reliability assurance at high thermal loads. With this aim in view FA designs with diverse intensifier grids are being developed.

Experimental research is being done in justification of thermal engineering reliability of such FAs and for determination of maximum permissible thermal loads. An ever-increasing amount of experimental data on critical heat fluxes (CHF), obtained using the FA models of new design has resulted in the need to store the data and arrange fast and convenient access to them using state-of-the-art computer technologies, i.e. database (DB) creation.

This study was aimed at creation of evaluated database on CHF in up-to-date design WWER FAs based on the experimental data obtained in 2009-2012 at JSC OKB Gidropress, JSC OKBM Afrikantov, NRC "Kurchatov Institute" and SSC RF-IPPE that in its turn suggested the solution of two problems. First – working out DB generation principles as a means of data storage and handling. Second – DB filling with reliable and complete, i.e. evaluated data.

2. The Principles of Database Generation

Until now the information on CHF experiments has been stored in a set of text files, with the inner structure defined by TEFOR format, designed by analogy with the international exchange format EXFOR for neutron cross-section data. For the urgent needs the information on experiments has to be addressed in a more structured as well as graphical format. The present-day tools and database storage and management media allow the required fundamental modifications to be made in order to generate a complete information space, both for experimental data storage and for retrieval of information in any form convenient for its subsequent use.

With this end in view the current structure and storage type were transformed to a relational structure of information storage. An essential complexity of experimental data representation is worth mentioning, these data in general format having any and all combinations of input and output parameters. It is also significant that the newly-developed storage structure primarily should perform a function of experimental data scalability. In other words, any newly supplied data should not fundamentally change the existing structure of information storage. The solution seems to be as follows. There is a set of data common for the majority of CHF experiments. It is stored in the form of a set of invariant relational tables. The set of parameters without a well defined structure and clear arrangement should stay in the same database in the form of list structures. Internal mechanisms/DBMS software manages both invariant data and general information. Note an essential point in the data arrangement: if with the course of time it turns out that part of list data acquires a more pronounced permanent form, then they can and must be converted to invariants. Therefore, a unified information environment is created, allowing registration of any experimental data with the complete textual or graphical interpretation of CHF experiment. At the output the user is offered a system for information retrieval in any form convenient for its subsequent use. It is important to note that this system appears to be open, i.e. providing a way for its continuous improvement.

In consideration of the foregoing a DB with a relational structure was worked out and implemented to store CHF data.

When designing the data structure the task was to eliminate information storage limitation in the existing formats for representation of physical experiments information. The DB with the new structure allows:

- textual, digital, graphical and other information to be entered;
- all characteristics, graphical data, documentation on the working units to be stored in the table format;
- an access to the experimental data to be provided as to a container (all information on the experiment can be represented by an integral object that can be easily extracted both for presentation to the user and for filtering (sampling) any part of the data);
- experimental results to be stored;
- all data to be stored in unified physical dimensions;
- information on new experiments with an arbitrary number of physical parameters to be added;
- all history of occurrence and further experimental data verification/ validation process to be reflected.

The new DBMS enables a new search engine to be developed for experimental data sampling (filtering) with the use of a standard query language SQL. The requirements for the search engine were formulated with due regard to the experience in accessing the information accumulated in EXFOR format, as well as the new concepts of users' requirements:

- real-time accessibility;
- expandability;
- scalability (the possibility to transfer the system to other DBMS standard platforms);
- capability to trace experimental data evolution over the entire time segment (from data acquisition and recording to their verification and acceptance as recommended ones) ;
- capability of integrated multiparameter search data sampling on various parameters (characteristics, experiment features, bibliographic references, authors etc.).

A search engine for CHF DB in present-day design WWER FAs was developed with account of the above requirements, which allows integrated multiparameter data sampling to be performed.

3. Experimental Data Evaluation

One of the major tasks in database creation is estimation of quality and validity of the data subsequently used in designing and verifying calculation methods and codes.

At the first stage of data evaluation the CHF DB experimental information completeness and consistency was reviewed in compliance with the regulatory document RD 03-34-2000 [1].

Drawing on the information on measuring instruments and fundamental measurement data processing techniques included in the CHF DB report documentation, calculated and expert analysis of experimental data errors was performed. It was shown, that the calculated estimates of CHF instrumental error and relative enthalpy in the CHF area were close to those stated in the report documentation.

The expert analysis of experimental data quality performed through comparison of the data for the identical FAs with regular SG (spacer grids), demonstrated good reproducibility and low scatter of CHF data comparing rather favorably with the calculated estimates of instrumental errors.

Refinement of FA model geometrical parameters was carried out by comparing the values of passage area and heated surface, heated and wetted perimeters calculated by the initial data (diameters and the number of rods, heated length, and channel flat-to-flat dimension) with the values given in the description of FA models. As a result of this comparative check such model description inaccuracies in the description of models as a wrong quantity of heated rods, a heated length, heated and wetted perimeters were revealed and corrected.

In order to specify the experimental conditions a confirmatory calculation of outlet and critical steam quality values was performed with the use of the duty parameters measured in the tests (water temperature at the inlet, pressure, flow rate, power) and a heat balance equation.

The incorrect data were rejected using the mathematical statistics methods. The essence of statistical data analysis consisted in the descriptions of sets of data for individual FA models with the use of linear regression and "two sigma" criterion [2] in order to detect gross errors in the measurements or the results of designer's processing of the tests. An example of such analysis is shown in Fig.1, where it can be seen that the experimental data for this FA model stay within two "sigmas", therefore, it means that incorrect values are lacking in this set of experimental data.

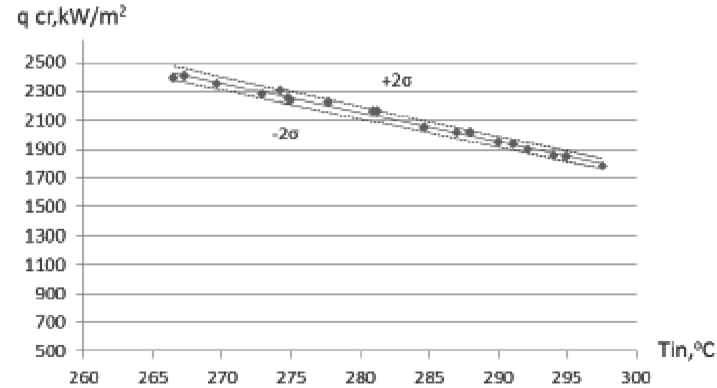

Figure 1. Critical heat flux dependence on the inlet temperature for bundle № 7 OKB "Gidropress" at P=12.25 MPa and RW=2500 (kg/м²c)

$\overline{\Delta}$ **= -0.01%, s = 0.95%**

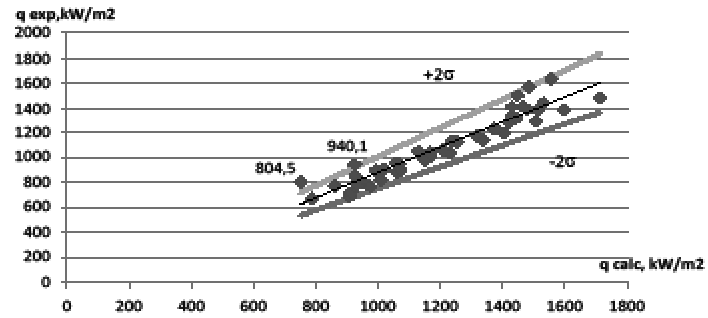

Figure 2. Comparison between the CHF experimental data with the calculation by Bezrukov formula for the TVSA-42 model

$\overline{\Delta}$ **= -0.45%, s = 7.32%**

However, there is not always an opportunity to construct a dependence of critical heat flux on one of the duty parameters with other parameters fixed, due to insufficient number of experimental points satisfying these conditions. In such cases for the data description the use was made of their comparison with the calculation results from Bezrukov formula [3] in (q_{cr}^{exp}) – (q_{cr}^{exp}) coordinates with subsequent approximation of the points obtained in this plane through liner regression and analysis of experimental data deviation from it.

Fig. 2 shows an example of experimental data calculation processing in the above-described methodology for the TVSA-42 model. As is evident from Fig. 2, there are only 2 points obtained at P=15.7 MPa and T_{in}=270°C that deviate from the approximating curve by more than 2 "sigmas". However, construction of the liner regression q_{cr}^{exp} (RW) by all the points obtained with these parameters, shows that these points cannot be qualified as incorrect ones either.

Strictly speaking, the empirical Bezrukov formula is only applicable to the full to WWER FAs equipped with regular spacer grids located with the pitch 255 mm. Even more so, since in the course of its deviation an assumption on thermohydraulic equivalence of bundle cells has been used, it operates with the cross-section average values of mass velocity and steam quality. Therefore, it can be used directly only for the analysis of CHF experimental data obtained using FA models with radial uniform power density. Nevertheless, the above methodology of this formula application helps in rejecting the data with a different grid type and arrangement in FA models, as well as in case of non-uniform power density.

Application of IPPE correlation [4], having a broader range of applicability as compared to Bezrukov formula, allowed the evaluated data range to be extended, and was a help in sorting out the experimental data, which gave rise to questions in the course of Bezrukov correlation application.

Thus, e.g. when evaluating the data for TVS-T1 by Bezrukov correlation an essential scatter of experimental data was obtained: s = 27.4%. In this case the experimental data themselves in $q_{cr}(x_{cr})$ coordinates demonstrate a noticeable scatter, that, apparently, accounts for a significant scatter in the event of their comparison with Bezrukov formula, where q_{cr} is calculated via direct substitution of experimental values x_{cr}.

When comparing the experimental data with the values of q_{cr}, calculated by a heat balance equation and the values of x_{cr}, determined using the IPPE formula, the scatter appears essentially lower.

The summary of experimental data evaluation results on CHF for the FA models with axial uniform power density is tabulated.

A report with a detailed description of methodology and experimental data evaluation results is incorporated into the DB.

Table 1. DB analysis results using OKB GP and IPPE correlations

FA model designation	OKB GP correlation		IPPE correlation	
	$\overline{\Delta}$, %	$\overline{\sigma}$, %	$\overline{\Delta}$, %	$\overline{\sigma}$, %
OKBM experiments				
TVSA-42	-0.45	7.32	-0.11	3.19
TVSA -72	-0.98	9.93	-1.45	11.79
TVSA -13	-0.5	7.19	-0.5	6.77
TVSA -19	-0.93	10.48	-0.22	4.52
TVSA -T3	-1.92	13.9	-0.17	4.35
TVSA -6	-0.49	7.04	-0.19	4.22
TVSA T1	**-3.07**	**18.37**	-0.17	4.05
IPPE experiments				
TVS-T1	**-4.77**	**27.4**	-0.93	7.47
TVS-2V2	**-2.59**	**14.49**	-1.31	9.78
TVS-2M	-1.05	9.89	-0.81	8.62
TVS-2-12	-1.62	11.15	-0.8	8.69
TVS-2-15	2.88	7.17	-0.11	3.74
PO-3V	0.71	9.86	-0.16	4.18
MV18-PRTs	-2.1	13.21	-2.83	13.83
MV19-PRTs	**-2.2**	**14.32**	-2.08	13.21
MV18-PRV	-1.72	12.35	-3.01	16.28
MV19-PRV	**-2.61**	**16.02**	-3.56	17.46
MK19-1	**-1.94**	**14.43**	-0.8	8.53
TVS-T2	-1.29	13.91	-1.31	7.94
NRC "KI" experiments				
TVS -2M(37ST-1.0B)	-0.29	5.64	-0.08	2.27
TVS -2M(37ST-1.0B2)	-1.19	10.06	-0.29	5.2
TVS-2M(37ST-1.0B) Vikhr	**-2.88**	**18.37**	-1.01	9.75
TVS-2M(37ST-1.0)SDPR	-0.71	7.62	-0.36	5.66
TVS-2M(37ST-1.3B)	-0.73	9.62	-0.26	3.68
TVS-2M(37ST-1.3B) Vikhr	**-3.55**	**18.08**	-0.85	7.56
TVS-2M(37ST-1.B) SDPR	**-4.21**	**21.33**	-1.1	9.61
19RU/3.53	-0.89	7.76	-0.71	5.29
OKB GP experiments				
BUNDLE №1	-1.11	10.25	-0.79	8.78
BUNDLE №2	-1.62	13.62	-0.39	5.55
BUNDLE №4	-1.52	12.62	-1.52	11.3
BUNDLE №7	-0.18	4.08	-0.1	3.06
TVS(7ST-1Vikhr)	-0.13	4.28	-0.09	3.61
TVS(7ST-3 Vikhr)	-0.15	3.95	-0.19	4.4
TVS (7ST-5SDPR)	-0.15	3.95	-0.07	2.77

4. Conclusion

1. A specification of format for CHF experimental information representation in FA models of new design in order to enter it into the BD was developed.
2. A relational structure for the storage of CHF data on WWER FA of up-to-date design was developed and implemented.
3. A pilot design of DB with a general approach to entering the new information into the data storage capable of storing textual, digital and graphical information in the structured form was created.
4. A user-friendly graphical user interface for BD handling was designed and implemented.
5. A flexible search system of experimental data sampling (filtering) was created.
6. An export of sampling results was implemented to excel spreadsheet format.
7. The completeness and compliance of BD experimental information with the RD 03-34-2000 regulatory document requirements was reviewed.
8. Incorrect data were rejected using statistical methods.
9. Comparison of the sets of CHF experimental data for different FA models was carried out.
10. The BD was supplemented with the data analysis functions (checking the consistency of output parameters with input parameters, comparison of CHF data with the calculation by empirical correlations).

As a result for the first time an evaluated data DB on CHF in the FA models of innovative design intended for calculation methods development, verification and improvement was created.

The created DB includes the data of 4183 experimental conditions obtained at 53 models of WWER FAs of various designs within the following parameter range:

- heated length – (1.25…4.2) m.;
- pressure – (6.9…18.3) MPa;
- mass velocity – (480…5080) kg/m^{2}s;
- water temperature at the inlet of FA model - (56…347) ^{o}C;
- critical heat flux – (290…4870) kW/m^2.

References

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