THERMAL ANALYSIS OF QM400 DRY STORAGE MODULE WITHOUT THERMAL BAFFLES

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ABSTRACT: *The first four QM400 dry storage modules with thermal baffles in Qinshan Phase-III CANDU-6 NPP were allowed to load the hexagonal fuel assemblies since Sep. 2009. Up to Oct. 2013, over 640 baskets filled with spent fuel assemblies were loaded into the 1# and 2# modules. When constructing above modules, multiple thermocouples were intentionally fixed in 1# module, to measure temperature on the surface of concretes, thermal baffles and stainless steel storage cylinders, aimed to better understand the performance of QM400 modules in decay heat remove. A large number of measured data had been collected and preliminary analysis results show the possibility to remove the thermal baffles, which can save budge and shorten the construction cycle for other modules in following few years. Thus, detailed quantitative analysis was proposed in 2014. This work consisted of two parts. First, benchmarking calculations based on measured temperature data were finished using authorized program CATHENA and commercial CFD software ANSYS FLUENT™, respectively. Critical parameters, such as heat transfer coefficient on concrete surface and etc, which may have great influence on the decay heat remove via air natural convection and solid conduction, were obtained. Best calculation parameters were determined for thermal calculations of QM400 module without thermal baffles using above codes. Second, multiple cases under normal and supposed accidental conditions were finished, demonstrating that all temperature criteria had been met though thermal baffles are removed. In addition, results from CATHENA and ANSYS FLUENT™ were compared, showing that good agreement of average temperature can be achieved via these two different codes. All results obtained had been submitted to NNSA to apply for a new license for the construction of new modules without thermal baffles.*

KEYWORDS: *Dry Storage, QM400, Thermal Baffle, Natural Convection, CATHENA, FLUENT.*

1. BACKGROUND OF QM400 DRY STORAGE MODULE IN QINSHAN PHASE-III NPP

Third Qinshan Nuclear Power Plant Co. Ltd. (TQNPC) in Zhejiang province of China has two CANDU-6 reactors loaded with hexagonal fuel assemblies. Spent fuel assemblies unloaded from the reactors should be first put into spent fuel pool for 6 years temporary storage, then removed into QM400 dry storage modules after the decay heat becomes much lower. First four QM400 dry storage modules in TQNPC were designed by AECL and were imported into China during the first decade of 20th century. It is a concrete monolith used to store fuel baskets which are filled with spent fuel bundles, and is mainly cooled by buoyancy-driven air flowing through 10 air intakes and 12 air outlets, which are symmetrically located on the lower and upper parts of module respectively. These air intakes, outlets and inner spaces of the module form a natural circulation to remove the decay heat generated by spent fuel assemblies. The overall layout and photo of the QM400 modules in TQNPC are shown in figure 1 and figure 2.

In order to keep the concrete temperature under limiting values and maintain the integrity of concrete structures of QM400[1], thermal baffles were bolted onto the majority of internal surfaces of concrete for the first four modules, which were made of cellular glasses. Conservative safety analysis using authorized program CATHENA were carried out to make sure that the concrete temperature of QM400 modules with thermal baffles were well controlled in normal and supposed accidental conditions. Meanwhile, 28 thermocouples were intentionally fixed on the outer and internal surfaces of concretes and thermal baffles at different positions, aiming to further validate the function of thermal baffles and reliability of calculation results of CATHENA before construction of following modules.

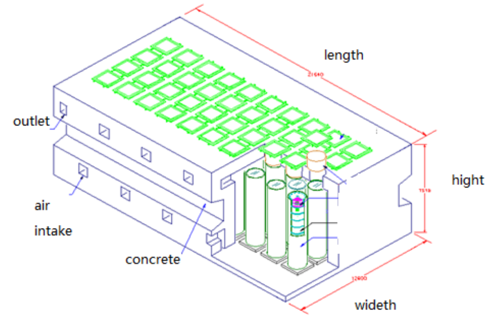


Fig. 1. Overall Layout of QM400 Dry Storage Module

Fig. 1. QM400 Modules in TQNPC

The first four modules were allowed to load spent fuel assemblies removed from spent fuel pool since Sep. 2009. Up to Oct. 2013, over 640 fuel baskets which were filled with spent fuel assemblies were loaded into 1# and 2# modules. During these 4 years, multiple measured temperature data had been collected under different environmental conditions, covering hot summer and cold winter, which are valuable to support the thermal analysis work before applying for license of construction of 5# and 6# modules. Engineers in TQNPC and SNERDI analyzed the measured data and found that the thermal baffles installed in the first four modules may be removed based on qualitative analysis. Thus, further quantitative analysis had been carrying out by engineers in SNERDI, to demonstrate that the concrete temperature can still be maintained under limiting values for QM400 modules in normal and supposed accidental conditions even thermal baffles are removed. In the following sections, detailed works finished in the past several years will be introduced. Temperature measurement system distributed in the 1# QM400 module will be first introduced, and the trends of temperature data will also be shown in section II. Two steps of detailed quantitative calculations, consisting of benchmarking calculations based on measured data and analysis of thermal performance of QM400 modules without thermal baffles using CATHENA and ANSYS FLUENT^{TM} will also be briefly presented in section III and IV. All results from above two codes had been submitted to NNSA to help TQNPC to apply for new license of construction of following modules without thermal baffles.

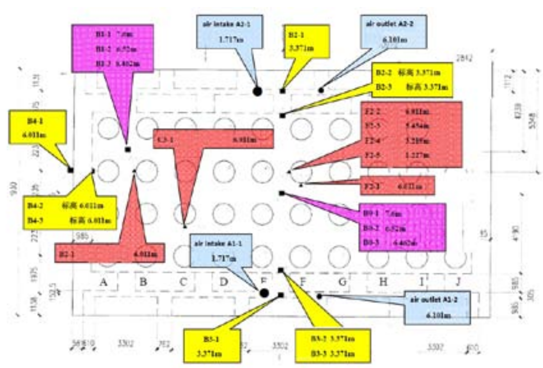


Fig. 3. Thermocouple Positions to Measure Temperature of Concrete and Thermal Baffles

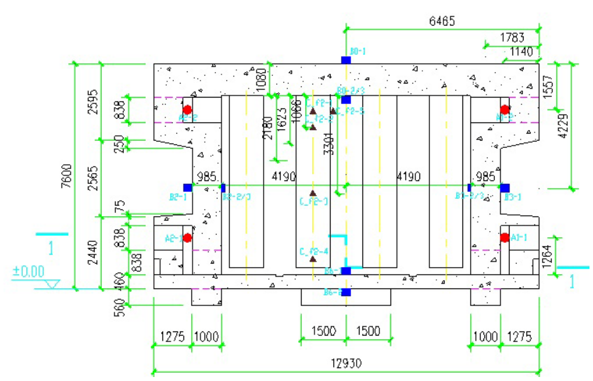


Fig. 4. Thermocouple Positions on the Out Surface of Stainless Steel Storage Cylinder F2

2. OPERATION HISTORY OF 1# QM400 MODULE

2.1 Temperature Measurement System

28 thermocouples were intentionally fixed in 1# QM400 module, which had thermal baffles bolted onto majority internal surfaces of concretes, aiming to measure the temperature of outer and internal surfaces of concrete, thermal baffles and outer surface of stainless steel storage cylinder F2. Usually, there are three thermocouples at one position. The first one is on the outer surface of concrete, the second on the interface of concrete and thermal baffle, and third on the internal surface of thermal

baffle. On the top ceiling of module, there are 2 positions (6 thermocouples in total) as is shown in figure 3, one in the center (the indices of thermocouples are B0-1, B0-2 and B0-3) and the other in the corner (the indices of thermocouples are B1-1, B1-2 and B1-3). On the four side walls, the position indices are B2, B3 and B4 (the indices of thermocouples are B2-1, B2-2, B2-3, B3-1, B3-2, B3-3, B4-1, B4-2 and B4-3). In addition, five thermocouples were fixed on the outer surface of stainless steel storage cylinder F2, as is shown in figure 4 (the indices of thermocouples are F2-1, F2-2, F2-3, F2-4 and F2-5), to obtain the axial temperature distribution under the influence of natural convection. The rest thermocouples were mainly fixed in the region of module air intakes and outlets, to measure the air temperature difference.

2.2. Qualitative Analysis of Measured Temperature Data

62 sets of temperature data had been collected from 2009 to 2013, including hot summers and cold winters. The highest recorded air temperature is 33.7℃. Linear fitting relations of measured temperatures on the surfaces of concrete and thermal baffles for all thermocouples had been obtained, which are functions of air temperature. Results are of great importance to guide the optimization of following QM400 modules.

Generally, the temperature on the surface of stainless steel storage cylinder F2 increases linearly as air temperature rises, as is shown in figure 5. Due to the effect of bottom-to-up buoyancy-driven natural flow, the axial temperature increases as thermocouple location increases. But the maximum temperature does not appear at the highest position (F2-1 and F2-2 are the highest positions), but at the position of F2-3, which is the second highest position, as is shown in figure 6. Figure 7 shows the trend of temperature variation on the outer and internal surface of thermal baffles on the top ceiling of module. In cold winter, the outer surface temperature is about generally 4.6℃ higher than that of internal surface. But as air temperature rises, the difference becomes smaller, and even become negative in hot summer, which means that solar irradiation was the primary contribution leading to the high temperature on the outer surface of concrete on the top ceiling, a nd thermal baffles did not work and was adverse for heat conduction through solid concrete. For the difference between outer and internal surfaces of concrete on the top ceiling as is shown in figure 8, it became smaller as air temperature went up, and still maintained positive in hot summer. Figure 9 and figure 10 show trends of temperature variation on the surfaces of concrete and thermal baffles on the side walls. These temperatures are well under limiting values, and are very regular, i.e., the maximum value appears on the outer surface of concrete, the minimum value on the internal surface of thermal baffle.

Thus, it is possible to remove thermal baffles bolted onto the four side walls because the temperature is usually far away from the temperature criterion. And for the thermal baffles on the top ceiling, it may prevent decay heat removing via heat conduction through solid concrete on the top ceiling in summer. Thus, engineers judged that it was possible to remove all the thermal baffles on the top ceiling as well.

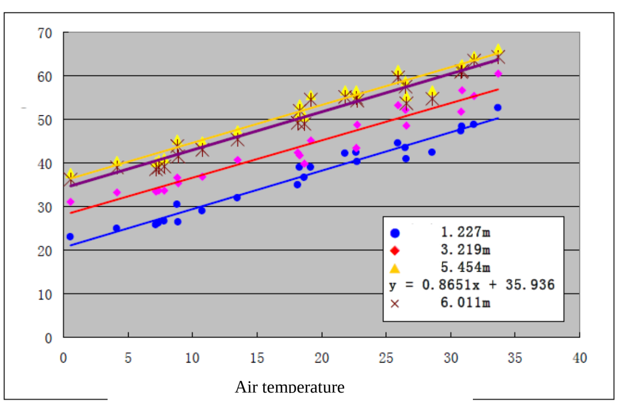


Fig. 5. Trends of Temperature Variation on the

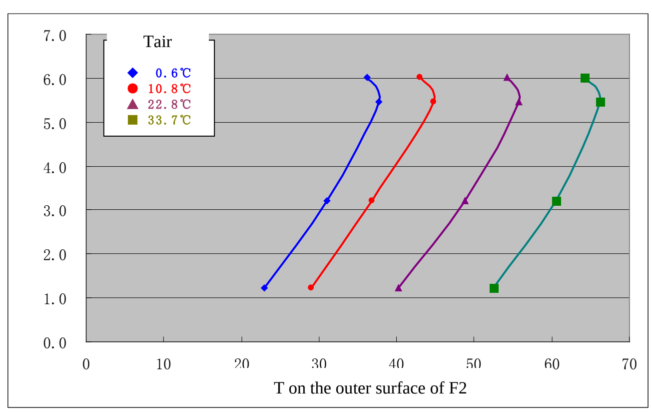
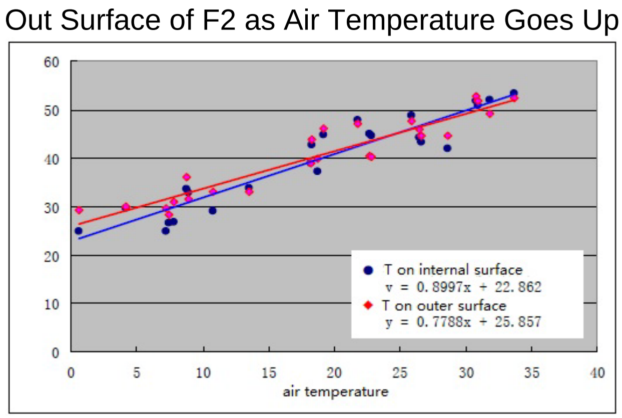


Fig. 6 Axial Temperature Distribution on the Outer



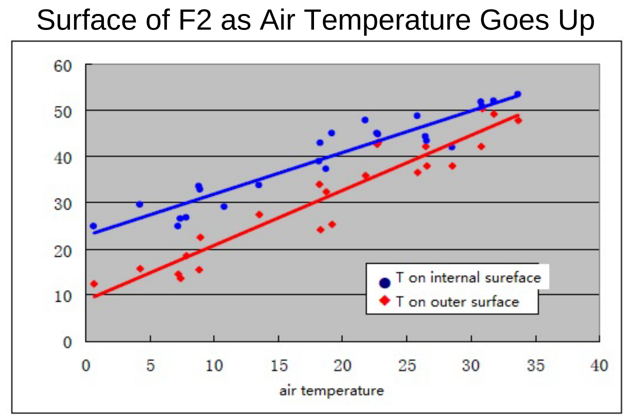
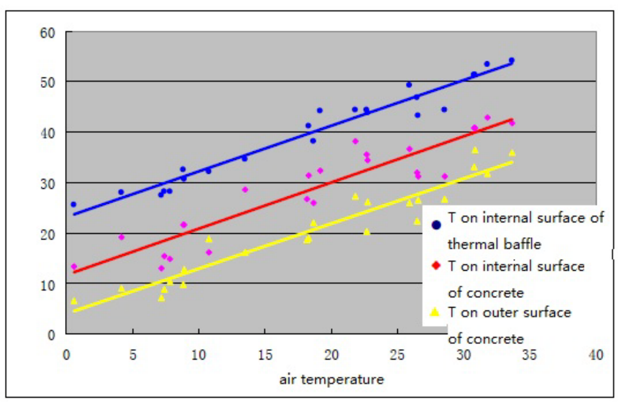


Fig. 7. Trend of Temperature on the Internal and Outer Surface of Thermal Baffle on the Top Ceiling

Fig. 8. Trend of Temperature on the Internal and Outer Surface of Concrete on the Top Ceiling



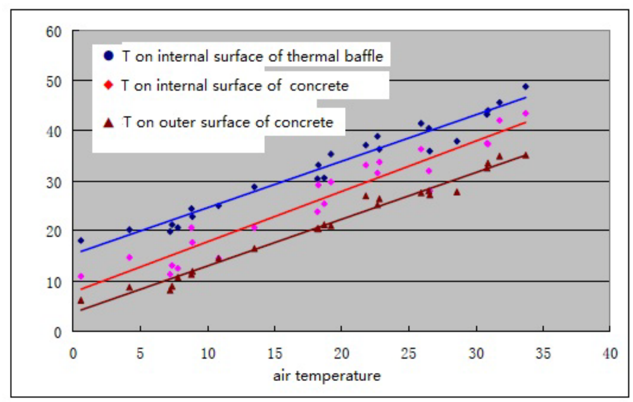


Fig. 9. Trend of Temperature on the Internal and Outer Surface of Thermal Baffle and Concrete on the Side Wall

Fig. 10. Trend of Temperature on the Internal and Outer Surface of Thermal Baffle and Concrete on the Side Wall

3. BENCHMARKING CALCULATIONS

Two steps of detailed quantitative evaluation work for QM400 module without thermal baffles were proposed and had been completed, including benchmarking calculations aiming to get best values of critical parameters based on measured data, such as heat transfer coefficient. These parameters will be used in following thermal analysis when QM400 module without thermal baffles operating in normal and supposed accidental conditions. Traditional thermal-hydraulic code CATHENA was used which was easy to obtain time-dependent results via fast calculations. The disadvantage of CATHENA is that the space discretization is too coarse to get the local surface temperature distribution. Thus, steady-state simulations employing commercial CFD code ANSYS FLUENT^{TM} were carried out to provide additional detailed temperature distribution contours when considering conjugate conduction.

3.1 CATHENA Code

CATHENA was first developed by AECL and was used to apply for license when QM400 dry storage modules were first imported into China. It is a one dimensional code, and generally applicable to one dimension fluid flow and two dimensions solid heat transfer calculations. The central region containing 16 stainless steel dry storage cylinders is modeled in CATHENA as is shown in figure 11. The air flow path is shown in figure 12. When used in analysis for QM400 module with thermal baffles, the overall solid region is discreted into very coarse meshes, as is shown in figure 13, in which thermal baffles are intentionally modeled. The parameters were first adjusted using measured data when air temperature was 33.7℃. Results comparison between CATHENA and measured data are shown in

Table 1. Results show that the good agreement is achieved, and enough margins can still be maintained. The main parameter adjusted was heat transfer coefficient on the outer surface of the module concrete.

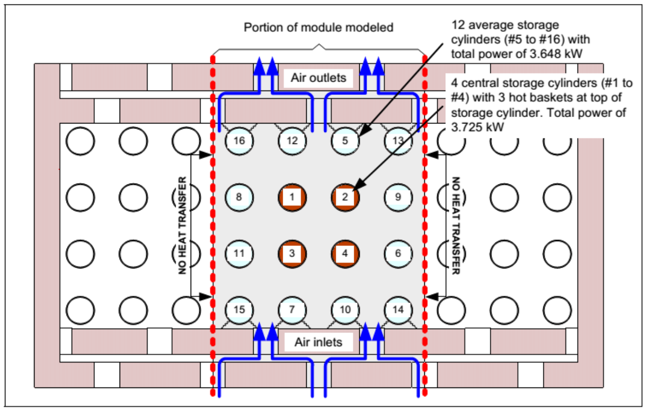


Fig. 11. Regions Modeled in CATHENA for Thermal Analysis for QM400 Module

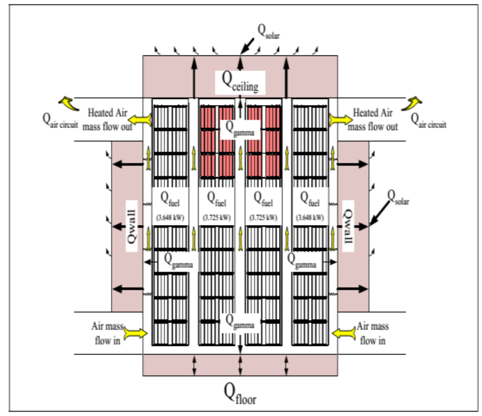


Fig. 12. Sketch of Flow Paths of Buoyancy-driven Air in QM400 Module

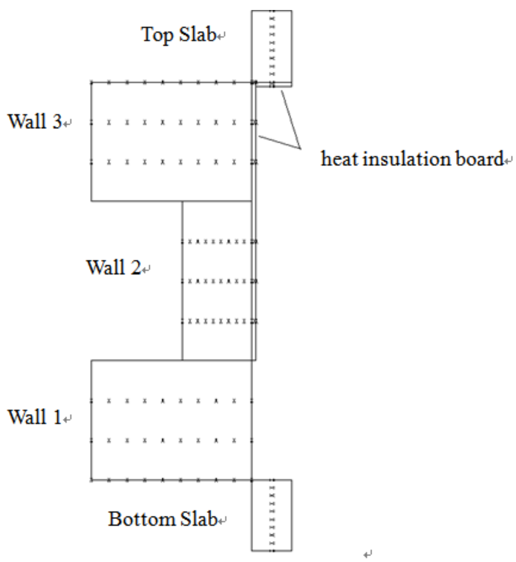


Fig. 13 Space Discretization of QM400 Module with Thermal Baffles Used in CATHENA

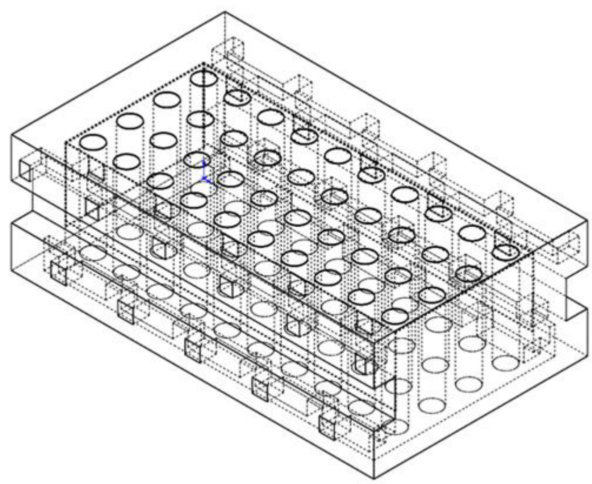


Fig. 14 Full-scale 3D Model Used in CFD Simulations Considering All Detailed Structures

Table 1 Comparison of Temperature between CATHENA and Measured Data

Thermocouple index	CATHENA calculated value (℃)	Measured value (℃)	Thermocouple index	CATHENA calculated value (℃)	Measured value (℃)
F2-2	69.8	63.9	B2-2	42.9	38.4
F2-3	69.5	65.4	B2-3	49.7	46.5
F2-4	57.3	55.2	B3-1	36.5	32.4
F2-5	50.3	50.2	B3-2	42.9	38.4
B0-1	49.1	48.9	B3-3	49.7	46.4
B0-2	56.6	53.2	B6-1	38.1	34.9
B0-3	62.5	52.1	B6-2	33.3	33.1
B2-1	36.5	35.1			

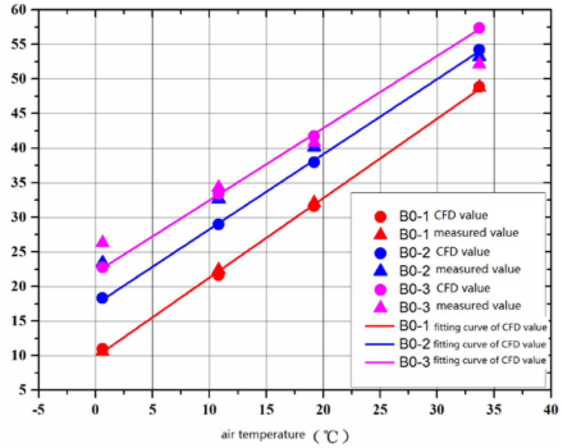


Fig. 15 Comparison of Temperatures between CFD Calculated Values and Measured Data at the Center Position on the Top Ceiling

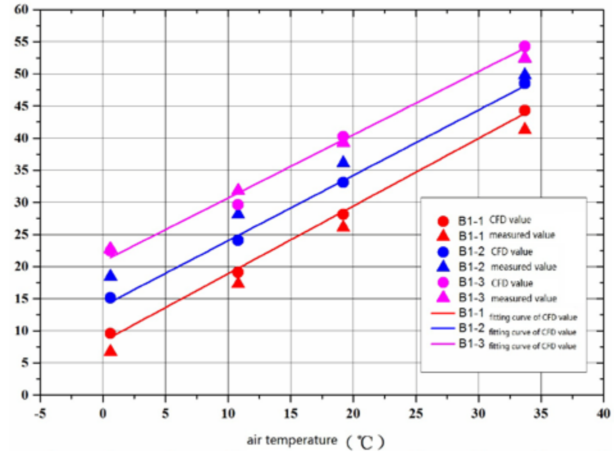


Fig. 16 Comparison of Temperatures between CFD Calculated Values and Measured Data at the Corner Position on the Top Ceiling

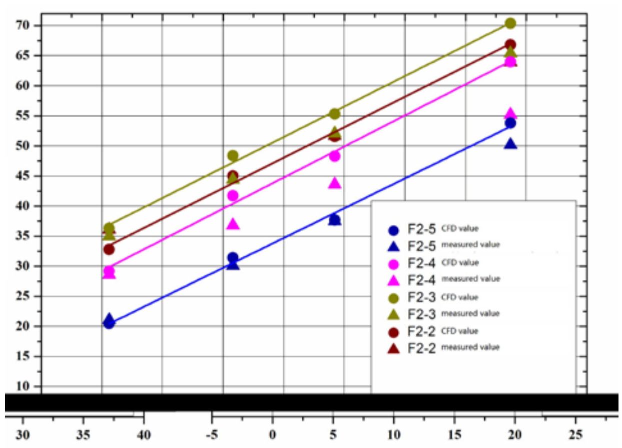


Fig. 17 Comparison of Temperatures between CFD Calculated Values and Measured Data on the Surfaces of Stainless Steel Storage Cylinder F2

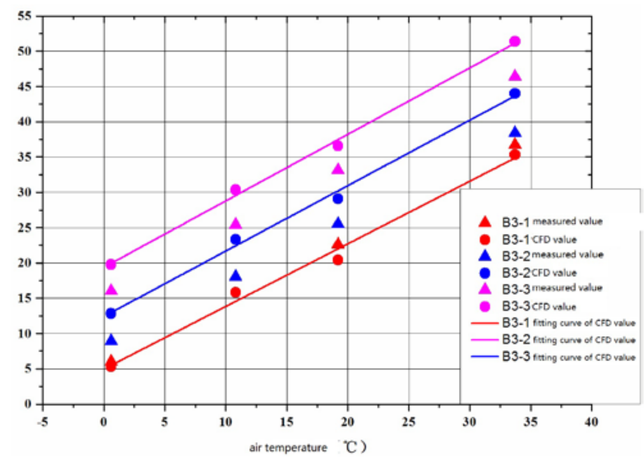


Fig. 18 Comparison of Temperatures between CFD Calculated Values and Measured Data on the Surface of Side Walls

3.2 ANSYS FLUENT™

Detailed CFD simulations using ANSYS FLUENT™ have also been carried out to get accurate prediction to support how many areas in which temperature may exceed limiting values. Full scale model shown in figure 14 were used and conjugate heat transfer was considered. Benchmarking simulations were first finished to adjust critical parameters. The difference is that four sets of measured data under typical air temperatures were used, i.e., 0.6℃, 10.8℃, 19.2℃ and 33.7℃. Temperature difference between outer and internal surfaces of thermal baffles is shown in Table 2. And comparison between CFD calculated value and measured data are shown in figure 15, figure 16, figure 17 and figure 18. It can be seen that well agreement had been achieved.

Table 2 Comparison of Temperature Differences between Outer and Internal Surfaces

Air temperature (℃)	Measured T difference at B2 (℃)	Calculated T difference at B2 (℃)	Measured T difference at B3 (℃)	Calculated T difference at B3 (℃)	Measured T difference at B4 (℃)	Calculated T difference at B4 (℃)
0.6	7.2	6.98	7.1	6.94	11.2	5.74

Air temperature (℃)	Measured T difference at B2 (℃)	Calculated T difference at B2 (℃)	Measured T difference at B3 (℃)	Calculated T difference at B3 (℃)	Measured T difference at B4 (℃)	Calculated T difference at B4 (℃)
10.8	6.7	7.05	7.4	7.02	10.5	5.48
19.2	6.3	7.56	7.6	7.47	9.9	5.93
33.7	5.7	7.40	8	7.37	9	5.72

4. THERMAL ANALYSIS OF QM400 WITHOUT THERMAL BAFFLES

After benchmarking calculations, CATHENA and ANSYS FLUENT™ were further used in following concrete temperature distribution of full loaded QM400 module without thermal baffles when operating in normal and accident conditions, which are listed in table 3.

The most conservative operation condition is hot summer when air temperature is 39.3℃. The CATHENA calculated variation curves of concrete temperatures on the outer and internal surfaces on the top ceiling, side walls and stainless steel storage cylinder when in normal operation are shown in figure 19 and figure 20. Figure 21 and figure 22 present the results respectively when intakes in one side of module are supposed to be all blocked. Results show that the concrete temperatures can be maintained under the limiting values for most of times during operation, except local regions on the top ceiling in which the temperature may exceed the limiting value for very short time. CFD results provide additional detailed temperature distribution to judge how many areas of local regions, as is shown in figure 23 and figure 24. The temperature calculated from CATHENA and ANSYS FLUENT™ was intentionally compared for operating conditions in summer. Good agreement was achieved as is shown in table 4.

Table 3 List of Normal and Accident Conditions of Safety Analysis for QM400 Modules without Thermal Baffles

Operation conditions		CATHENA	ANSYS FLUENT™
Normal operation in summer (air temperature is 39.3℃)		Y	Y
Accident operation	One intake blocked	Y	Y
	Intakes in one side all blocked	Y	Y
Normal operation in winter		Y	N
Accident operation	One intake blocked	Y	N
	Intakes in one side all blocked	Y	N

Table 4 Comparison of CATHENA and CFD Calculated Concrete Temperature in Summer

Operation conditions in summer	T calculated by CATHENA (℃)	T calculated by ANSYS FLUENT™ (℃)	T calculated by CATHENA	T calculated by ANSYS FLUENT™ (℃)
Normal operation	62.6	62.7	62.6	61.7
Supposed accidental operation when intakes in one side blocked	65.0	65.5	65.9	64.4

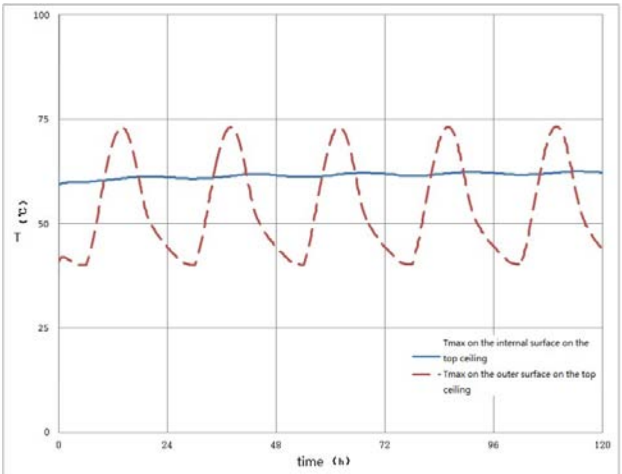


Fig. 19 Variation of Outer and Internal Concrete Temperatures on the Module Top Ceiling under Normal Operation in Summer

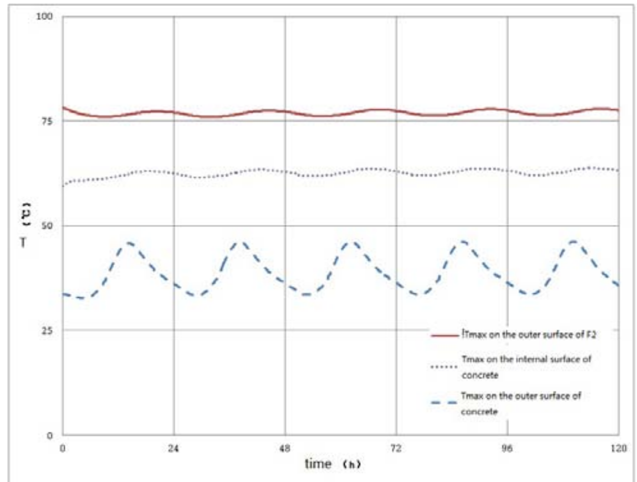


Fig. 20 Variation of Outer and Internal Concrete Temperatures on the Surfaces of Side Wall under Normal Operation in Summer

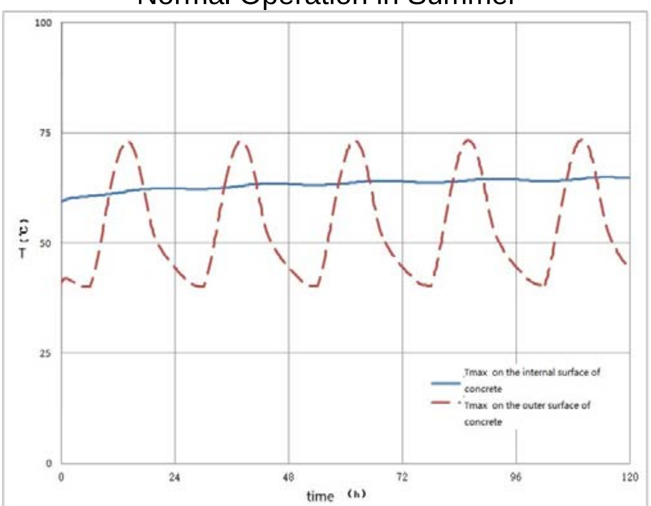


Fig. 21 Variation of Outer and Internal Concrete Temperatures on the Module Top Ceiling under Accident Operation in Summer

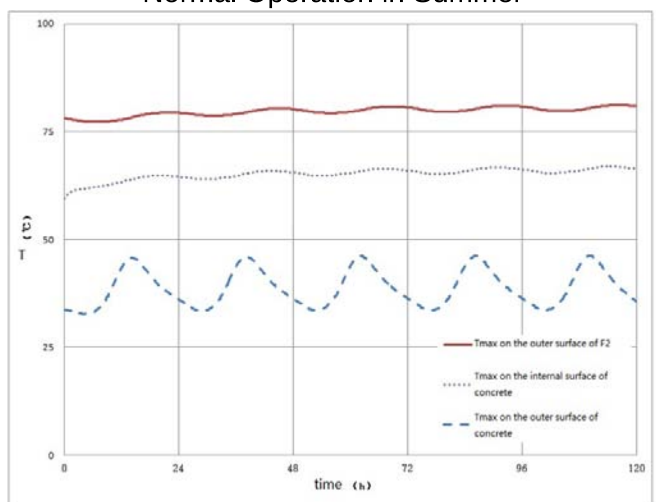


Fig. 22 Variation of Outer and Internal Concrete Temperatures on the Surfaces of Side Wall under Accident Operation in Summer

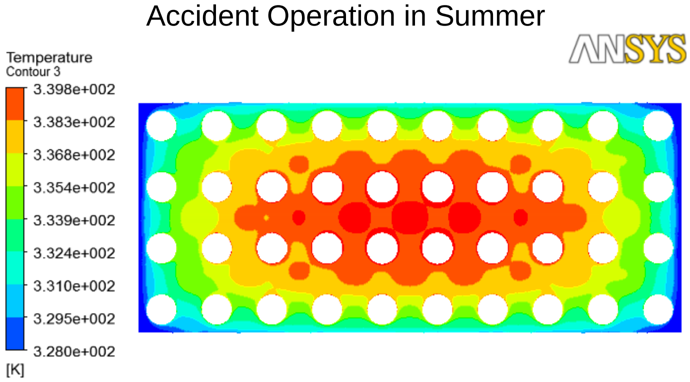


Fig. 23 Detailed Temperature Distribution on the Surface of Module Top Ceiling Obtained by CFD Calculation

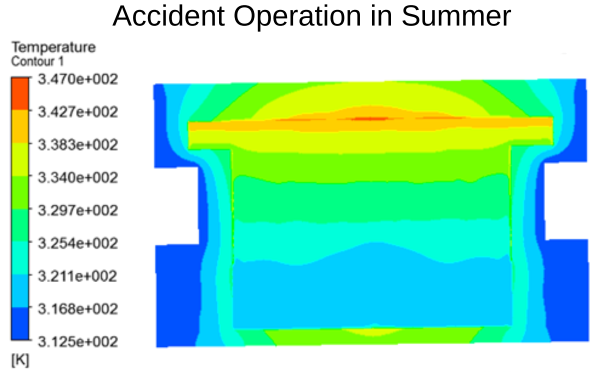


Fig. 24 Detailed Temperature Distribution on the Surface of Module Side Wall Obtained by CFD Calculation

5. CONCLUSIONS

A large number of measured data have been collected and preliminary analysis results as functions of air temperature show the possibility to cancel the thermal baffles when constructing following modules. Thus, detailed analysis including quantitative thermal calculations was proposed. This work consists of two parts. First, benchmarking calculations for 1# module based on operation temperature data were finished using CATHENA and ANSYS FLUENT^{TM}, respectively. . Best calculation parameters were obtained for the thermal calculations of QM400 module without thermal baffles using above codes. Second, multiple cases under different conditions were finished to demonstrate that all temperature criteria had been met. In addition, results from CATHENA and ANSYS FLUENT^{TM} were compared, showing that CATHENA had more margins and FLUENT^{TM} can provide useful local information. All analysis results from above two codes had been submitted to NNSA to apply for new licensing for the construction of new modules without thermal baffles.

6. REFERENCE

[1] ACI 349-97, Code Requirements for Nuclear Safety Related Concrete, American Concrete Institute.