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Experimental Research and Optimization of Measurement Accuracy of Nitrogen and NOx Sensors at Different Positions in CHINA Ⅵ Post-processing System

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Abstract

The design test verifies whether the downstream NOx sensor meets its design accuracy requirements on the CHINA VI mainstream box and barrel post-treatment. As a result of the test, the measurement accuracy of the downstream NOx sensor disposed on the rear end surface of the tank meets the requirements; the measurement accuracy of the downstream NOx sensor disposed on the rear tapered surface of the barrel does not meet the requirements. The simulation results of the barrel structure show that the ammonia uniformity of the rear cone surface is 0.957, but the ammonia uniformity of the local position of the back cone surface is poor, which cannot meet the requirements of the nitrogen oxide sensor. The uniformity of ammonia distribution on the straight pipe of the tail pipe is greater than 0.97, and the local ammonia heterogeneity gradually decreases with the increase of the length of the tail pipe. The position optimization test results show that the position of the downstream NOx sensor is changed from the tapered surface to the straight pipe section of the tail pipe, and the NOx sensor layout point meets the requirements of the downstream NOx sensor with the minimum distance of 190 mm from the barrel-type post-processing cone. A post-cavity mixer was designed to make the current downstream NOx sensor position ammonia uniformity 0.996, and there is no local high ammonia problem. This solution can also solve the measurement accuracy of the downstream NOx sensor.

Keywords

Heavy duty diesel engine; NOx sensor position; DOC-DPF-SCR; Box and barrel;ANSYS ICEM CFD.

1. Introduction

The extremely strict national VI regulations for heavy-duty diesel engines are coming, which not only greatly reduces the emission limit and OBD limit, but also puts forward high requirements for the timeliness and accuracy of diagnosis of nitrogen and oxygen sensors [1-4]. As the most important component of the diesel engine OBD diagnosis, the downstream nitrogen oxygen sensor can accurately measure the actual nitrogen oxide under any working condition, which is of great significance to correctly reflect the catalytic converter fault and ensure that the emissions of in-use vehicles meet the requirements of national VI regulations.

Two nitrogen oxygen sensors need to be used in the sixth heavy-duty diesel engine to collect the nitrogen oxide concentration before and after the aftertreatment tank. They are defined as upstream nitrogen oxygen sensor and downstream nitrogen oxygen sensor respectively. The upstream nitrogen oxygen sensor is arranged on the straight pipe between the turbine rear and DOC-DPF-SCR after-treatment assembly. Its main function is to measure the level of nitrogen oxides emitted by the original diesel engine. There is no interference of gas flow caused by urea injection, and its accuracy can meet the design requirements. The downstream nitrogen oxygen sensor is arranged near the rear end face of the after-treatment assembly. The front section is the rear end face of the SCR carrier, and the rear end is the tailpipe flange of the external tailpipe. The location of its distribution points is affected by the flow rate change caused by the diameter change of the tank and the uniformity of ammonia distribution, so the measurement accuracy of nitrogen and oxygen concentration is difficult.

DOC-DPF-SCR after-treatment assembly box type and barrel type are two common structural forms in China VI. The nitrogen oxygen sensor in the two structures is installed according to the Continental nitrogen oxygen sensor installation specification [5]. The difference between the two structures and the requirements of the supporting users determines that the downstream nitrogen and oxygen sensors are not consistent. In order to determine whether the layout of downstream nitrogen and oxygen sensors of the two structures meets the accuracy design requirements, the design test verifies its measurement accuracy and optimizes the layout of the unsatisfactory conditions.

2. The establishment of Test Device

Fig. 1 and Fig. 2 show the general installation layout of the test bench, and Fig. 3 and Fig. 4 show the layout of the test bench. Including 4L/10L diesel engine, AVL 460/KW electric dynamometer, AVL AMAI60 gas analyzer, can measure NOx and other gases. Horiba 6000FT-E ammonia leakage analyzer, AVL 735S fuel consumption meter, full-room air conditioning temperature control, secondary intercooling control intake temperature. Box and barrel post-processing systems.

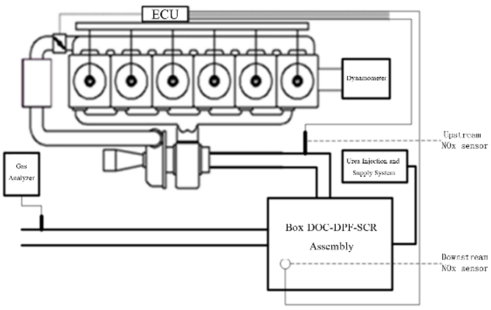

Figure 1 Layout diagram of NOx test downstream of box-type post-treatment

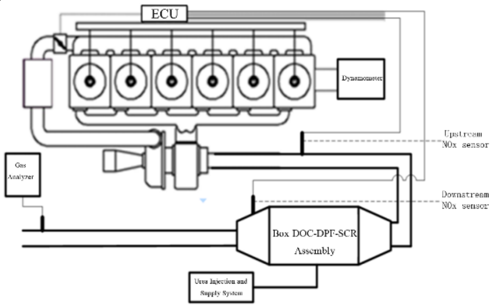

Figure 2 Layout diagram of nitrogen and oxygen test downstream of barrel-type post-treatment

The test engines are Weichai WP10 and WP4.6N diesel engines with models of WP10H400E62 and WP4.6NQ220E61, and their main parameters are shown in Table Ⅰ.

The test fuel is national VI diesel. The engine oil is 15W/40 CI-4, which conforms to GB 11122. The antifreeze is Mobil - 15 ℃.

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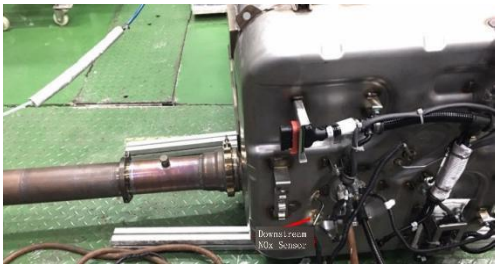

Figure 3 Layout of NOx test bench at downstream of box-type post-treatment

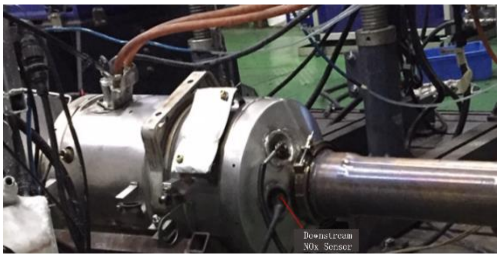

Figure 4 Layout of NOx test bench at downstream of barrel-type post-treatment

TABLE I. MAIN TECHNICAL PARAMETERS OF TEST ENGINE

Project	Company	WP4.6NQ220E61	WP10H400E62
type	-	Supercharged intercooler	Supercharged intercooler
Number of cylinders	-	4	6
Total displacement	L	4.58	9.5
Rated power	kW	162	294
idling	r/min	700	600±50
Rated speed	r/min	2300	1900
Maximum torque	N·m	800	1800

Post-treatment tank for test includes 10L box-type and 4.6L drum-type DOC-DPF-SCR assembly. The NOx sensor used in the test is the Continental 2.8 generation NOx sensor. The urea metering device for the test is Bosch DeNOx2.2 non-air-assisted urea pump, and the injection pressure in the pump is 0.9MPar. Urea is an aqueous urea solution with a mass concentration of 32.5%, and its physical parameters comply with DIN700070 standard.

3. Test method

Post-treatment is arranged on the test bench that can meet the cycle of the sixth national emission standard, and the downstream nitrogen and oxygen precision test is designed and verified.

Whether the downstream nitrogen and oxygen sensor accuracy test meets the requirements, the NOx results measured by the gas analysis equipment in the test bench are used as the basis for comparison to determine whether its accuracy meets the requirements. The precision test method of nitrogen and oxygen sensor is as follows:

a) Five working points are selected from the 5th, 9th and 10th rated points of the national standard cycle WHSC [1], and the temperature before SCR is 200 ℃.

b) The ammonia-nitrogen ratio of urea injection volume is set at 0, 0.7 and 1.1 respectively. Measure after each operating point is stable for at least 20 minutes and the nitrogen and oxygen value is stable. Record the average value in 20 seconds. Record the NOx value measured by the bench analyzer in ppm. The downstream nitrogen oxygen sensor measures the NOx value in ppm. The recording frequency is 10HZ.

c) Select two identical nitrogen oxygen sensors to repeat the above tests.

d) Evaluation standard: the absolute deviation between the measured value of downstream nitrogen and oxygen and the measured value of bench gas analyzer is ≤ 10% or ≤ 10ppm (when NOx is ≤ 90ppm).

4. Experimental result

4.1. Experimental Result of Box-type

The results are shown in Table Ⅱ. According to the evaluation criteria, it is judged that the location of nitrogen and oxygen sensors downstream of the box-type post-treatment meets the accuracy measurement requirements.

The rear cavity space formed by the rear end face of the box-type after-treatment carrier and the after-treatment end face is large, there is basically no airflow disturbance, the ammonia distribution uniformity is good, and the measured value is basically consistent with the measured value of the bench analyzer.

TABLE II. DISTRIBUTION AND MEASUREMENT RESULTS OF BOX TYPE NITROGEN OXYGEN SENSOR

Operating point	Ammonia nitrogen ratio	Twice mean value of downstream nitrogen and oxygen/ppm	Average value of analyzer twice/ppm	% of deviation/value ppm
WHSC-5	0	1766	1745.5	1.2%
	0.7	865	840	2.9%
	1.1	352.5	324.5	7.9%
WHSC-9	0	1093	1086	0.6%
	0.7	255	268	4.9%
	1.1	3	3	0
WHSC-10	0	1448	1421	1.9%
	0.7	905	933	3.0%
	1.1	368	349.5	5.0%
Rated point	0	1200.5	1177	2.0%
	0.7	705	685	2.8%
	1.1	389	371.5	4.5%
200℃	0	399.5	397.5	0.5%
	0.7	228.5	228	0.2%
	1.1	175	176	0.6%

4.2. Experimental Result of Barrel-type

The results are shown in Table Ⅲ. According to the evaluation criteria, it is judged that the location of nitrogen and oxygen sensors downstream of the barrel post-treatment does not meet the accuracy measurement requirements.

It can be seen from Table Ⅲ that:

a) At the working point WHSC-10, the ammonia nitrogen ratio is 0.7 and 1.1, which exceeds the design accuracy requirements. When the ammonia nitrogen ratio is 0.7 and 1.1 at the rated point, it exceeds the design accuracy requirements. The accuracy of the downstream nitrogen and oxygen sensor does not meet the requirements when the torque, exhaust temperature and rotational speed are large under both conditions and there is urea injection

b) When the ammonia-nitrogen ratio is 0 and the load is medium and low, the measurement results of the downstream nitrogen and oxygen sensor are basically similar to those of the bench gas analyzer, meeting the design accuracy requirements.

c) The measured value of high speed and high load with urea injection volume, especially when the injection volume is large, has a large gap with the bench gas analyzer, and cannot meet the design accuracy requirements. The maximum measurement accuracy deviation of downstream nitrogen oxygen sensor even reaches 41.7%.

Through searching the research data of bucket structure, it is found that the structure has good flow velocity uniformity, the pressure loss at the conical surface at the outlet end is large, and the ammonia mixing uniformity before and after SCR is slightly poor [6]. For the above reasons, the ammonia uniformity at the position of the after-treatment cavity is slightly poor, so that the measurement accuracy of the nitrogen oxygen sensor arranged at the position of the rear cone is difficult.

TABLE III. MEASUREMENT RESULTS OF BUCKET NITROGEN OXYGEN SENSOR

Operating point	Ammonia nitrogen ratio	Downstream nitrogen and oxygen twice average ppm	Average value of analyzer twice ppm	% of deviation/value ppm
WHSC-5	0	1641	1620	1.3%
	0.7	521	497	4.6%
	1.1	4	7	3.0
WHSC-9	0	834	845	-1.3%
	0.7	261	265	-1.5%
	1.1	16	14	2.0
WHSC-10	0	1285	1310	-1.9%
	0.7	554	494	10.8%
	1.1	200	155	22.5%
Rated point	0	1246	1210	2.9%
	0.7	527	452	14.2%
	1.1	199	116	41.7%
200℃	0	149	143	4.0%
	0.7	116	115	0.9%
	1.1	86	83	3.5%

5. Simulation analysis

In order to find the appropriate location of nitrogen and oxygen sensors, the ANSYS ICEM CFD software is used to simulate and analyze the velocity uniformity and ammonia uniformity of the barrel post-processing [7-11].

5.1. Geometric Model

Create a 3D model in Creo, and then import it into ANSYS to process the model and perform hexahedral mesh division [12-15]. See Fig. 5 and Fig. 6.

Figure 5 3D model

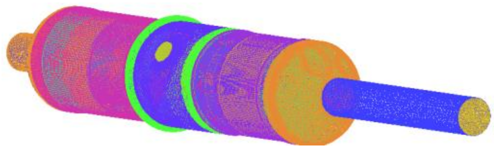

Figure 6 Grid division

5.2. Solver settings

See Table Ⅳ for model setting and boundary condition setting. Three urea jets are set at the urea nozzle position. See Fig.7 for spray trajectory. The spray particles are directly sprayed into the porous plate and the lower shell of the mixer. Under high temperature conditions, most particles evaporate and are splashed and decomposed into small particles.

TABLE IV. PARAMETER SETTING

physical model			boundary condition			
turbulence model	***Pressure velocity coupling***	***Wall conditions***	***entrance***	***Thermal boundary***	***Inlet temperature***	***Urea injection***
Realizable k-epsilon	SIMPLE	standard wall function	constant mass flow	hconvection =10W/m2-K epsilon=0.55	539℃	561mg/s

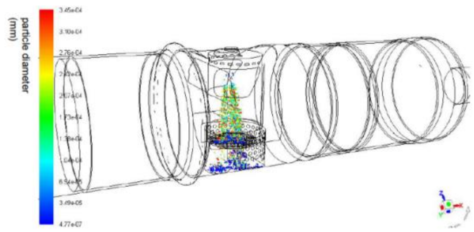

Figure 7 Urea spray Track

5.3. Calculation results

Air flow uniformity

It can be seen from Fig. 8 that the air velocity at the rear end face changes from about 5m/s to about 17m/s after passing through the cone, and then to about 60m/s after entering the straight pipe section. Although the gas flow rate changes, the gas flow uniformity at the same section is good.

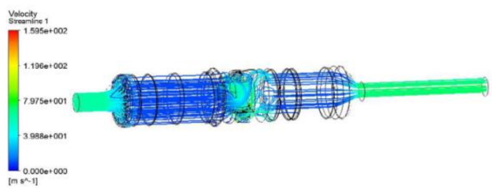

Figure 8 Air flow path

Ammonia uniformity

From Fig. 9 and Fig. 10, At the conical position, the ammonia uniformity is 0.957, but at the center of the box, that is, the local position of the nitrogen oxygen sensor probe, the ammonia uniformity is poor. The arrangement of nitrogen and oxygen sensors at the conical surface can not avoid the uneven ammonia in the center of the box, so the arrangement of the conical surface can not meet the requirements of nitrogen and oxygen sensor accuracy.

After entering the straight pipe section, the uniformity of ammonia is gradually improved. Moreover, the problem of local high ammonia decreases with the increase of exhaust pipe length.

Considering the supporting and cost factors, the straight pipe of exhaust tailpipe should not be too long. Too long straight pipe may cause space layout restrictions of different supporting manufacturers, and too long straight pipe may cause material costs to rise.

Intercept 70mm, 110mm, 150mm, 190mm and 500mm from the rear end face respectively, and check the ammonia uniformity at 5 positions, as shown in Fig. 10.

a) The uniformity of ammonia at five positions is 0.968, 0.973, 0.977, 0.980, 0.987. The uniformity of ammonia increases with the distance from the cone.

b) The local nonuniformity of ammonia is obvious at 70mm and 110mm, and the local area of nonuniformity of ammonia decreases significantly from 150mm.

c) Considering the uniformity of ammonia and the size of ammonia local area, verify whether the accuracy of nitrogen and oxygen sensor meets the requirements from three positions of 110mm, 150mm and 190mm. The ammonia uniformity of the three positions is greater than 0.97, and the ammonia uniformity gradually increases with the distance. In order to determine whether the three positions meet the accuracy requirements of the nitrogen and oxygen sensor, it is necessary to design a test to verify.

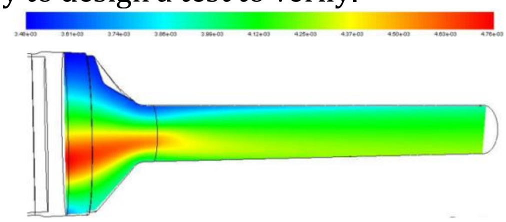

Figure 9 Ammonia uniformity distribution

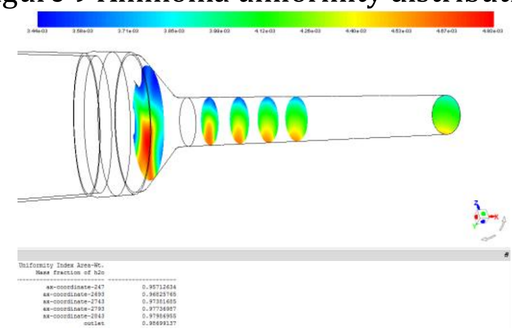

Figure 10 Ammonia Uniformity at Several Sections

6. Position optimization

6.1. Test design

Add three measuring points of nitrogen oxygen sensor on the tail pipe of the after-treatment exhaust at 110mm, 150mm and 190mm from the rear end face, which are respectively defined as position C, position B and position A. Measure the deviation between the nitrogen and oxygen values at three positions and the bench gas analyzer. Find the minimum distance position point that meets the accuracy requirements. The test method is the same as above. See Fig. 11 for the schematic diagram and Fig. 12 for the rack layout.

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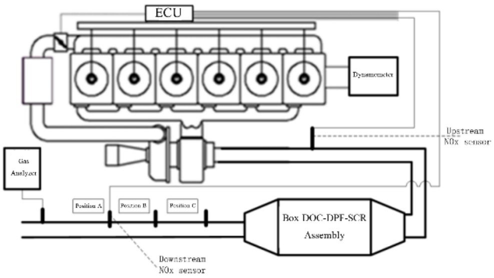

Figure 11 Layout diagram of nitrogen and oxygen test bench at downstream of barrel post-treatment

Figure 12 Layout of Position Optimization Bench

6.2. Position optimization test results

Carry out the nitrogen oxygen sensor accuracy test for position C, position B and position A. See Table Ⅴ, Table Ⅵ and Table Ⅶ for test results.

TABLE V. MEASUREMENT FAILURE POINT AT POSITION C

Operating point	Ammonia nitrogen ratio	Downstream nitrogen and oxygen twice average ppm	Average value of analyzer twice ppm	% of deviation/value ppm
WHSC-10	one point one	one hundred and thirty	one hundred and fifty-two	14.5%
Rated point	one point one	one hundred and twenty-two point five	one hundred and forty-eight point five	17.5%

TABLE VI. MEASUREMENT FAILURE POINT AT POSITION B

Operating point	Ammonia nitrogen ratio	Downstream nitrogen and oxygen twice average ppm	Average value of analyzer twice ppm	% of deviation/value ppm
WHSC-10	one point one	one hundred and thirty-six	one hundred and fifty-three	11.1%

TABLE VII. NITROGEN AND OXYGEN ACCURACY TEST RESULTS AT POSITION

Operating point	Ammonia nitrogen ratio	Downstream nitrogen and oxygen twice average ppm	Average value of analyzer twice ppm	% of deviation/value ppm
	0	one thousand six hundred and four	one thousand six hundred and one point five	-0.2%
WHSC-5	zero point seven	five hundred	five hundred and thirteen	2.5%
	one point one	three	six	three

WHSC-9	0	eight hundred and thirty-nine	eight hundred and thirty-five	-0.5%
	zero point seven	two hundred and forty-nine	two hundred and fifty-nine	3.9%
	one point one	twenty-eight point five	thirty	5%
WHSC-10	0	one thousand two hundred and twelve	one thousand two hundred and ten point five	-0.1%
	zero point seven	four hundred and ninety-seven	four hundred and ninety-five point five	-0.3%
	one point one	one hundred and forty-nine	one hundred and fifty-four	3.2%
Rated point	0	one thousand two hundred and twelve	one thousand two hundred and nine point five	-0.2%
	zero point seven	five hundred and twenty-one	five hundred and seventeen	-0.8%
	one point one	one hundred and thirty-eight	one hundred and forty-six	5.5%
200℃	0	one hundred and seventy	one hundred and seventy-two	1.2%
	zero point seven	one hundred and eleven	one hundred and twelve point five	1.3%
	one point one	seventy-seven	eighty-one	four

It can be seen from Table Ⅴ that there are still two operating points at position C that do not meet the requirements. But the accuracy error is much smaller than the value measured at the rear cavity position.

It can be seen from Table Ⅵ that there is one working point at position B that does not meet the requirements. And the accuracy error amplitude is decreasing with the increase of distance.

It can be seen from Table Ⅶ that the measurement accuracy of nitrogen oxygen sensor at position A meets the requirements. The uniformity of ammonia at this location is 0.98, and the uneven area of ammonia is small.

It can be seen from Table Ⅲ and Table Ⅶ that, on the whole, in addition to meeting the requirements for the measurement accuracy of nitrogen and oxygen at position A of straight pipe section, the measurement accuracy is also much higher than that of the rear chamber nitrogen and oxygen sensor.

Therefore, position A is a 190mm distance position that can meet the measurement accuracy of the nitrogen oxygen sensor and is the minimum distance from the end face of the rear cavity.

7. Structural optimization

According to the simulation and test results at the rear exhaust straight pipe, as long as the ammonia uniformity reaches 0.98 at the section of the rear chamber conical tube nitrogen and oxygen sensor, and the uneven area of the ammonia partial distribution is small, the accuracy of the nitrogen and oxygen sensor can meet the requirements.

In order to meet this requirement, it is necessary to add a mixer behind the rear chamber carrier and in front of the nitrogen oxygen sensor to improve the ammonia uniformity and local ammonia non-uniformity.

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7.1. Design of rear chamber mixer

A mixer is designed, and its structure is shown in Fig. 13.

Figure 13 Structure of rear cavity adder

This mixer has been patented. The structure is composed of swirl blades and perforated pipes. The swirl blade can further mix the local uneven ammonia gas coming out from the rear face of SCR carrier. The perforated pipe forces the change of the flow path, further increasing the uniformity of ammonia mixing and eliminating the problem of local high ammonia.

7.2. Simulation analysis results

The simulation analysis results are shown in Fig. 14 and Fig. 15. After the air flow passes through the rear chamber mixer, the air flow is discharged in a swirling way. The calculated result of ammonia uniformity at the downstream nitrogen oxygen sensor position section is 0.996. Compared with Fig. 10 and Fig. 15, it can be seen that after adding the rear chamber mixer, there is no local non-uniformity of ammonia.

Therefore, no matter the uniformity of ammonia or the local high level of ammonia, the improvement effect is more obvious than that on the straight pipe position. The measurement accuracy of downstream nitrogen and oxygen sensor can be solved by designing this mixer scheme.

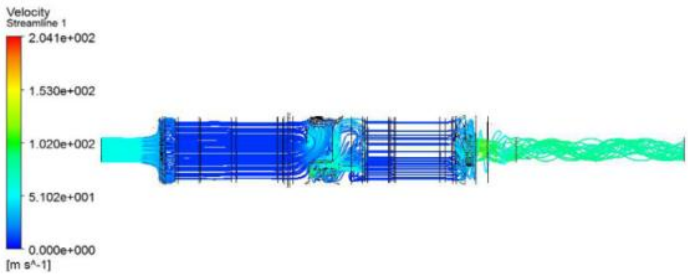

Figure 14 Air flow path of rear chamber booster

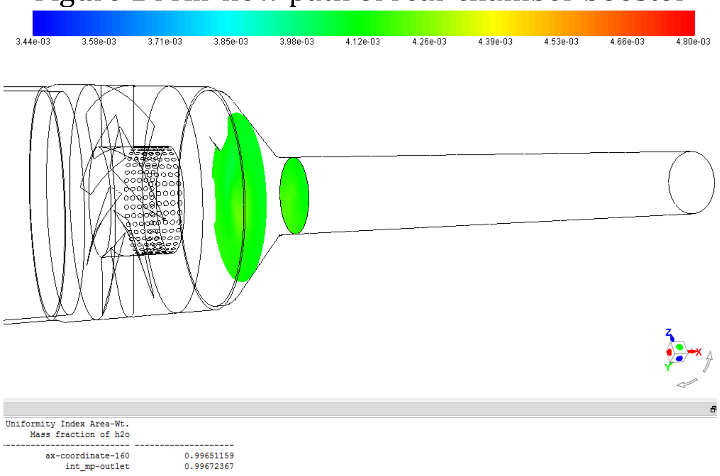

Figure 15 Ammonia uniformity of rear chamber booster

8. Conclusion

a) The uniformity of ammonia in the chamber after box-type post-treatment is good, and the air flow rate is uniform. The downstream nitrogen and oxygen sensor precision measurement of the post-processing of this structure meets the design requirements.

b) When there is no urea injection or ammonia in the barrel post-treatment, the measurement accuracy of the nitrogen oxygen sensor at the conical surface of the rear chamber meets the requirements. However, in the presence of ammonia, it can not meet the accuracy requirements under the working condition of high torque and speed, and even reach the accuracy deviation of 41.7%.

c) According to the CFD simulation of bucket after-treatment, the flow velocity from the rear cone to the exhaust pipe gradually increases, but the flow velocity uniformity at the same section is good; The local position uniformity of ammonia in the center of the rear cone is poor. The uniformity of ammonia in the straight exhaust pipe increases with the distance from the straight pipe to the rear end face, and the local uniformity of ammonia gradually decreases.

d) The position optimization test results show that the measurement accuracy of the downstream nitrogen oxygen sensor can meet the requirements when it is arranged at least 190mm away from the rear end section.

e) Without changing the position of the existing downstream nitrogen oxygen sensor, it is necessary to add a mixer at the rear chamber. The simulation results show that both the uniformity of ammonia and the local high of ammonia are significantly improved than the straight pipe section.

f) The nitrogen and oxygen sensor is arranged at 190mm of the rear exhaust straight pipe, or a rear chamber mixer structure is added, which can solve the measurement accuracy problem of the bucket DOC-DPF-SCR post-treatment rear chamber nitrogen and oxygen sensor.

Acknowledgments

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