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Evaluating the performance of a water-cooled scooter engine through a 3-D numerical and experimental anaysis

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Abstract. In this study, a 3-D numerical model of a 400c.c four-stroke single-cylinder, water-cooledscooter engine is established and evaluated through computational fluid dynamics (CFD) with a conjugated heat transfer scheme to show the temperature distribution of the engine. The flow field of the water jacket is also observed, and the correlation between the heat transfer performance and flow field is discussed. In order to observe the real coolant flowing through the inside of the water jacket and make a comparison with the numerical results, we establish a transparent water jacket model using a 3-D printer. For the sake of developing the water jacket guidelines, we arrange the number of the gasket holes to acquire different flow fields and thermal results.

1. Introduction

Without a doubt, the temperature of internal combustion engines plays a crucial role in engine performance and endurance. If the temperature goes too high, it causes damage to the combustion chamber, the cylinder liner, the valves, the valve seats, and the plug seat. On the other hand, if the temperature goes too low, it decreases the efficiency of lubrication and combustion. Hence, keeping engines operating under adequate temperature conditions is a critical issue that needs to be addressed.

2. Theoretical Model

In this paper, a 3-D numerical model for a 400c four stroke single cylinder water-cooled scooter engine was established, as shown in Figure1. The yellow region is the cooling jacket; the black region is the gasket, and the other region is the engine parts.Different gaskets are shown in Figure2. Case1 is the original design from the scooter manufacturer. In order to optimize the flow field in the water jacket, the distribution of holes was rearranged in different ways on the gasket, as shown incases 2 to 12.

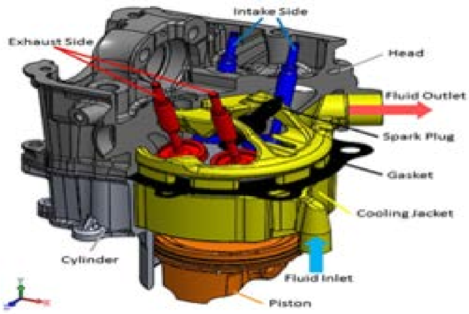

Figure 1. The layout of engine model

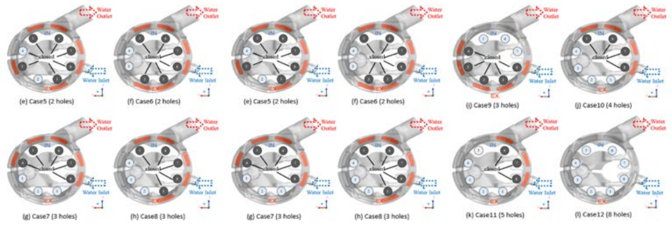

Figure 2. Different arrangements of gasket holes.

2.1. Governing Equations

The mass conservation equation is given by:

$$\frac{\partial \overline{u}_j}{\partial x_j} = 0 \tag{1}$$

The momentum equation is given by:

$$\rho \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_j\right) = -\frac{\partial \overline{P}}{\partial x_j} + \left(\mu + \mu_T\right)\frac{\partial}{\partial x_j}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{2}$$

The energy equation related to the fluid part (coolant water) is given by:

$$\rho C_p \frac{\partial}{\partial x_j}\left(\overline{u_j T}\right) = \overline{u_j}\frac{\partial \overline{P}}{\partial X_j} + \overline{u_j' \frac{\partial P'}{\partial x_j}} + k_f \frac{\partial^2 T}{\partial x_i^2} - \rho C_p \frac{\partial}{\partial x_j}\left(\overline{u_j' T'}\right) \tag{3}$$

For the solid part (engine), the heat conduction equation may be expressed as a Laplace equation:

$$\nabla^2 T = 0 \tag{4}$$

3. Experimental Set-Up

In order to observe the flow field inside the engine, the experimental set-up is shown in Figure 3.It consists of a water pump, a Karman vortex flow meter, and a transparent 3-D printed water jacket model,which is shown in Figure 3.The transparent 3-D printed water jacket modelcontains two parts, a cylinder side and a cylinder head side, in orderto separate and readily adjust different hole arrangements.We useda sharp tool to scarify the holes on the mat andchange the distributions of these holes with different casesas mentioned above.These flow rate and velocity values are shown in Table 1.

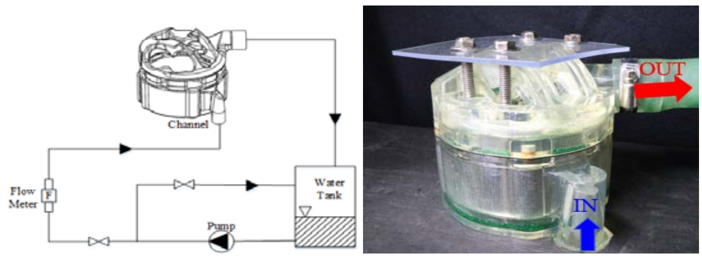

Figure 3. Experimental set-up and 3-D Printed water jacket.

Table 1. Water volume flow rate of each case

	case1 (Original design)	case2	case3	case4	case5	case6	case7	case8	case9	case10	case11	case12
hole open	1,2	2,3	1,3	1,4	2,4	3,4	2,3,4	1,2,3	5,6,7	1,2,3,4	1,2,3,4,5	all
$\dot{Q}$ (L/min)	28	30	29	32	32	32	32.5	30	34	33	34.5	35
V_{in} (m/s)	2.05	2.20	2.12	2.34	2.34	2.34	2.38	2.20	2.49	2.42	2.53	2.56
Increase of volume rate (%)	----	7.14	3.57	14.2	14.2	14.2	16	7.14	18.1	17.2	19.6	20.2

4. Results and Discussion

4.1. Model Validation

In order to verify the simulation, the real experimental data should be compared with the numerical results. The experimental data for Case 1and Case 2 wereprovided by the scooter manufacturer. The locations forthe temperature sensors are indicated in Figure. 4. For both cases, there are 13 sensorsallocated on the cylinder head and 4 sensorsallocated on the cylinder. It is shown in Table2that the calculated temperature data were in good agreement with the experimental data within a 10% difference.

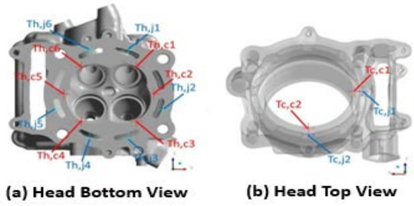

Figure 4. Location of thermal couples.

Table 2. Difference between experiment and simulation of case 1 and case2.

Case 1

Position head	T(°C) Experiments	Simulation	Error (%)
Tc,1	131.6	142	7.90
Tc,2	115.6	107.4	7.43
Tc,3	109.5	104.8	4.29
Tc,4	111.9	108.3	3.21
Tc,5	118.6	113.4	4.38
Tc,6	144	154.6	7.36
Tj,1	89.5	88.8	0.78
Tj,2	91.2	83.8	8.11
Tj,3	92.5	84.4	8.75
Tj,4	95.5	86.4	9.52
Tj,5	96.4	89.4	7.26
Tj,6	98.2	92.4	5.90

Position cylinder	T(°C) Experimental	Simulation	Error (%)
TC1	100.2	109.8	9.58
TC2	102.2	97.8	4.29
Tj,1	99.5	103.4	3.91
Tj,2	92.6	92.5	0.10

Case 2

Position head	T(°C) Experiments	Simulation	Error (%)
Tc,1	129.2	139.5	7.97
Tc,2	113.2	105.1	7.24
Tc,3	107.2	103.2	3.91
Tc,4	109.5	105.3	3.83
Tc,5	116.2	109.8	5.50
Tc,6	139.5	147.6	5.80
Tj,1	87.5	84.8	3.08
Tj,2	90.2	82.1	8.90
Tj,3	91.2	82.8	9.11
Tj,4	94.2	84.1	9.32
Tj,5	95.3	86.4	9.33
Tj,6	96.2	88.6	7.91

Position cylinder	T(°C) Experimental	Simulation	Error (%)
TC1	99.2	106.7	7.56
TC2	100.2	96.52	3.69
Tj,1	99	100.14	1.15
Tj,2	91.5	91.4	0.11

4.2. Flow Field for Different Gasket Openings

The total water volume flow rate and the percentage of water passing through the open holes for the different gasket openings are shown in Table 3. As a result, the gasket hole closer to thewater jacket exitwill cause more coolant to pass through. Figure 5 shows that the flow rates in Case 4, Case 5, and Case 6 are less in the cylinder-head side of the water jacket as compared with the flow rates in Case 1, Case 2, and Case 3.Figure 8 also shows that more holes are opened with the exception of Case 8. It can be observed that these cases where the flow rates passing through hole No. 4 to hole No. 8 to the exit are lower than for other holes, especially in Case 9, where approximately 44% of the total coolant flows through hole No. 6, which is closest to the exit. This phenomenon concurs with the previous cases discussed above, which caused deficieniesy in the heat coefficient. In Figure 5, we can see the side view of the real flow field in the water jacket and experimental flow field. For the experimental flow field, it issimilar to the simulated streamline depicted in Figure.5. Using this method, we can validate the numerical results.

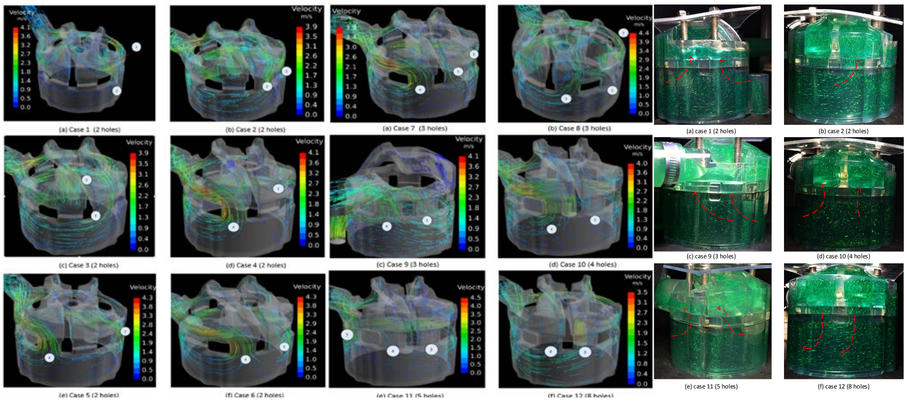

Figure 5. Numerical flow field (Case 1 – Case 12) and experimental flow field

Table 3. Flow rate percentage of different hole.

	!̇ #$%& (L/min)	(̇ #$%& (m/s)	Hole	!̇ (L/min)	!̇/!̇ # (%)
Case 1 (original design)	28	2.05	1	15.28	54.6
			2	12.43	44.4
Case 2 (2 holes)	30	2.20	2	15.57	51.9
			3	13.98	46.6
Case 3 (2 holes)	29	2.12	1	18.27	60.3
			3	10.73	39.6
Case 4 (2 holes)	32	2.34	1	13.69	42.8
			4	18.27	57.1
Case 5 (2 holes)	32	2.34	2	14.01	43.8
			4	17.98	56.1
Case 6 (2 holes)	32	2.34	3	12.38	38.7
			4	19.58	61.2
Case 7 (3 holes)	32.5	2.38	2	9.52	29.3
			3	7.34	22.6
			4	15.73	47.5
Case 8 (3 holes)	30	2.20	1	14.4	47.9
			2	4.8	15.7
			3	10.8	35.4
Case 9 (3 holes)	34	2.49	5	8.5	25
			6	15.2	44.6
			7	10.3	30.3
Case 10 (4 holes)	33	2.42	1	9.8	28.6
			2	1.93	5.6
			3	5.67	17.2
			4	15.7	47.6
Case 11 (5 holes)	34.5	2.53	1	10.5	30.5
			2	1.24	3.6
			3	2.34	6.8
			4	3.58	10.4
			5	16.73	48.5
Case 12 (8 holes)	35	2.56	1	3.03	8.7
			2	2.72	7.8
			3	2.48	7.1
			4	2.18	6.2
			5	3.63	10.4
			6	6.67	19
			7	3.36	9.5
			8	10.9	31.1

4.3. Heat Transfer Coefficient for Different Gasket Openings

The heat transfer coefficient distribution and average heat transfer coefficient for different gasket openings are shown as Figure 7 and Table. 4.However, the corresponding average heat transfer coefficients are reduced from 3 to 11%. The resultshows that the heat transfer coefficient for Case 2 is increased around 4.2 % more than other cases.There are many important components located at the cylinder head such as the exhaust valves, intake valves, and valve seats. Therefore, the heat transfer efficiency of the cylinder head should be taken into account. As the value of the convection coefficient h becomes lower, a high temperature distribution will result.

Table4. Average heat transfer coefficient for different gasket openings.

		case1 (Original design)	case2	case3	case4	case5	case6	case7	case8	case9	case10	case11	case12
open hole		1,2	2,3	1,3	1,4	2,4	3,4	2,3,4	1,2,3	5,6,7	1,2,3,4	1,2,3,4,5	all
h	Cylinder head	20322	21275	20712	17334	17167	16846	16480	20888	11922	16828	15675	16118
	Cylinder	13271	13809	13497	14350	14875	15472	15095	13710	15701	14785	15177	13260
	Average	16543	17247	16814	15696	15884	16068	16352	17044	13920	15734	15429	14604
	Deference %	—	4.25	1.64	-5.11	-3.98	-2.87	-5.18	3.03	-15.85	-3.77	-6.73	-11.72

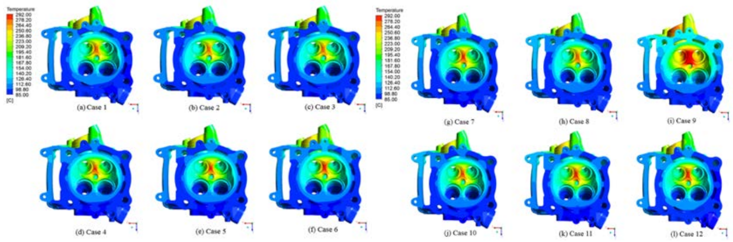

Figure 6. Cylinder Head Temperature (Case 1 – Case 12).

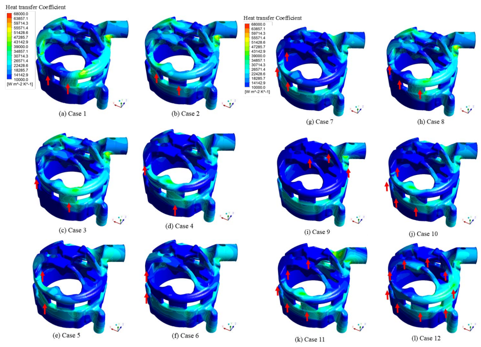

Figure 7. Heat Transfer Coefficient (Case 1 – Case 12).

4.4. Cylinder Head Temperature for Different Gasket Openings

For all cases, the highest temperature region existed between the two exhaust valve seats in the combustion chamber, as shown in Figure 8. Compared with all of the other cases, there was the most homogeneous and highest heat transfer coefficient around the exhaust side in Case 2. Therefore, the temperature could be lower than in the other cases.

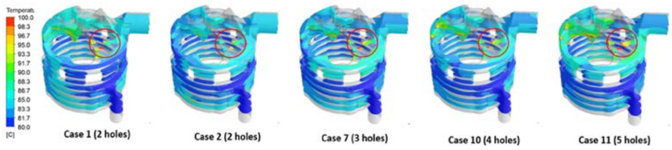

Figure 8. Hot Spot in Water Jacket of Cylinder Head.

4.5. Different Arrangements of Gasket Holes Cause Various Mean Temperature on the Exhaust Valve Seat

Table5 showsthe different mean temperatures on the exhaust valve seat because of different arrangements of the gasket holes. The locations of the exhaust valve seats are depicted in Figure 9. The seat closest to the plug is marked in red, and the one closest to the valve chain is marked in blue. The region where the exhaust valves and valve seats area are touched is shown in yellow. Table 5 shows that the temperature for Case 2 on the plug side is not the lowest; the temperature on the chain side is the lowest. Also, the value of the difference between theplug and chain temperature is only 0.3 degrees, which is the smallest in all Cases.

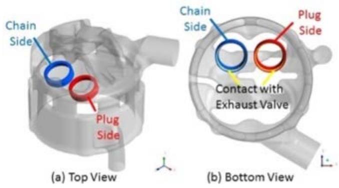

Figure 9. Location of exhaust valve and seat.

Table.5 Exhaust valve seat mean temperature.

	$\overline{T}_{plug}$ °C	$\overline{T}_{chain}$ °C	$\left\lvert \overline{T}_{plug} - \overline{T}_{chain} \right\rvert$ °C
Case1	289.6	293.7	4.1
Case2	290.1	290.4	0.3
Case3	289.7	294.5	4.8
Case4	291.7	296.1	4.4
Case5	294.9	294.1	0.8
Case6	298.2	295.8	2.4
Case7	296.3	297.1	0.8
Case8	288.8	293.7	4.9
Case9	330.8	333.7	2.9
Case10	291.5	296.4	4.9
Case11	297.1	301.7	4.6
Case12	292.1	294.7	2.6

5. Conclusion

According to the results, there are some valuable conclusions as addressed below:

1. Through the 3-D printed water jacket model, we were able to observe the actual streamline in the water jacket. In addition, this result could be compared with the numerical flow field results for the sake of validation of the numerical simulation.
2. As the number of holes on the gasket was increased from 2 to 8, the flow rates increased by as much as 20.2%. After the coolant flowed into the water jacket, it was divided into two parts. One part of the fluid entered the cylinder head in a clockwise direction, while the other part entered the cylinder head in a counter-clockwise direction. We found that the coolant flow concentrated through the hole closest to the exit. For this reason, setting the hole close to the exit had a negative effect on performance.
3. Compared to the original design, which was Case 1, the flow rate for Case 2 increased by 7.14 %, and the average heat transfer coefficient increased by around 4.25%. For cases 7 to 12, the flow rates increased by 16 to 20%, while the average heat transfer coefficients reduced by around 5.1 to 11.7%. As a result, it could be inferred that the flow rate does not have direct correlation with the heat transfer coefficient, but the flow field does.
4. The highest temperature region exists between the two exhaust valve seats in a combustion chamber. Case 2 exhibited the lowest and most uniform temperature distribution around the region of the exhaust valve seats.
5. To obtain high performance of a water jacket in a water-cooled engine, the gasket holes should be arranged away from the exit.

Acknowledgements

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