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Original Research

Verification of the performance of the paddle wheel swirl meter using numerical simulation and experimental test

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ABSTRACT

Considering the importance and the effect of the rotating flows inside the cylinder on the performance of internal combustion engines and the direct effect of these flows on reducing the amount of greenhouse gas emissions and reducing fuel consumption, it is essential to investigate the characteristics of these flows. Therefore, the issue of ensuring the performance of the swirl meters and the accuracy of the results obtained from the measurement becomes essential. Due to the lack of a specific and standard reference and the loss of performance of the swirl meter over time, it is necessary to have a method and means for its verification and calibration. The present study was carried out to validate the performance of the paddle wheel swirl meter and design a new and easy method for its calibration. The results simulation performed by the dynamic mesh method are very close to the results obtained from the experimental test and have high accuracy, because it directly simulates the performance of the paddle wheel swirl meter, but on the other hand, it requires a very high computational cost. According to the results obtained from the numerical solution and experimental test, the simultaneous use of the calibration equipment along with the correlation relationship is suggested as a fast and high-precision method.

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1- Introduction

Internal combustion engines that produce power by burning fossil fuels cause the production of pollutants such as carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NOx), sulfur dioxide (SO2), and solid particles, which cause environmental pollution and create greenhouse effects on the atmosphere. One of the important factors in controlling the combustion process and the emission of exhaust gasses is increasing the level of turbulence before combustion by the movement of the fuel mixture inside the cylinder, which can be caused by secondary flows. These rotational flows play an important role in many engineering applications such as modern gas turbines, aircraft propulsion, and internal combustion engines [1-3].

So far, several measurement methods have been presented, including optical measurement methods, paddle wheel, and impulse swirl meter, as well as numerical simulation methods based on CFD[1], each depending on the type of rotational flow (swirl & tumble) to predict its value. Cui et al. [4] investigated the effect of the rotation angle on the performance of the swirl meters to optimize and expand the measurement range. Using CFD analysis, they investigated the performance of the swirl meter for three different rotation angles and found that the larger the angle of incidence, the stronger the rotational flow.

Yang et al. [5], to establish a direct relation between the measurement with the flow bench and the actual flow inside the cylinder, examined the flow from the inlet port to the cylinder. For this purpose, they analyzed the polar velocity profile in the port and the polar physical distance using numerical simulation. They observed that the polar velocity profile is strongly influenced by the physical characteristics of the polar distance and found that useful information can be extracted from the physical distance and polar velocity profile in the field of entrance port design.

Da Costa et al. [6] investigated a single-cylinder optical engine to provide an experimental method and a numerical analysis to describe the tumble flow inside the cylinder. They compared high-speed 2D velocimetry with numerical simulation and proposed the k-ε RNG[2] turbulence model to simulate in-cylinder rotational flow because the numerical results showed better agreement.

Hong et al. [7], aimed to compare the measured results and the predicted results of the in-cylinder tumble flow of a 4-stroke single-cylinder engine with the LDV[3] method. They made this comparison based on the relations obtained by dividing the sum of rotational velocity vectors by the sum of crankshaft angles and observed a good level of agreement between the results of these two methods.

El-Adawi et al. [8] studied the cylinder head geometry of an internal combustion engine to investigate the characteristics of the in-cylinder flow. They compared the two methods of Ricardo flow bench and the paddle wheel with the PIV method and reported that there is a good level of agreement between Ricardo's test bench and the paddle wheel with optical method (PIV[4]).

Wahono et al. [9] tested a small engine cylinder head to investigate the flow of fuel-air mixture inside the internal combustion engine cylinder. They measured the rotating flow inside the cylinder under the condition of 100-300 mmH2O pressure difference using the steady flow bench and impulse swirl meter. They found that the greater the pressure difference, the lower the flow coefficient and discharge coefficient.

Jamil et al. [10] compared existing measurement methods to better understand the rotating flows inside the cylinder and their measurement methods. Therefore, they

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[1] Computational Fluid Dynamics
[2] Renormalization Group
[3] Laser Doppler Velocimetry
[4] Particle Image Velocimetry

investigated optical methods (PIV), traditional methods (Paddlewheel & Impulse torque meter), and CFD analysis. They reported that the PIV method is the easiest and most common method for the three-dimensional flow detector inside the cylinder, and the flow detector particles have no effect on the distortion process and the overall movement of the flow. They stated that the paddle wheel method and the traditional method as a whole, due to the placement of physical interfaces in the flow path, causes a decrease in the quality of the rotating flow and, as a result, a decrease in the measurement accuracy. They also stated that CFD analysis, including the use of Ansys Fluent software, provides very accurate results compared to experimental findings.

Ikpe et al. [11] performed a CFD analysis using Ansys Fluent software for the valve opening of 8 mm to investigate the swirl and tumble flow on the thermal performance of the engine. They found that the increase in the swirl coefficient causes the formation of uniform swirling streamlines and expands the flaming surface of the fuel-air mixture in the cylinder wall.

Masi et al [12] investigated the reliability of their new paddle wheel for tumble rotation in high-speed engines. They compared their new paddle wheel measurement methods with the old L and T-shaped flow bench methods and also used CFD analysis. The new paddle wheel consisted of two perpendicular rotating rings that could measure a larger area of the roller flow. They reported that the new swirl meter has angular momentum sensitivity at least 2 times lower than Ricardo's T-shaped. Due to the interaction between the vortex of the tumble flow inside the cylinder and the T-shaped Ricardo swirl meter, there is a high level of deviation from the angular momentum, and this issue has caused more concern about the reliability of this type of swirl meter and finally, they reported that a new swirl meter is a reliable tool for measuring tumble flow.

Zhao et al. [13] predicted the in-cylinder flow field in a direct injection engine with the Bi-RNN[1] model and compared it with the PIV experimental method. They reported that the proposed model can correctly predict the mass flow and vortex motions from the first suction stroke to the compression stroke. In measuring the amount of rotation, it is clear that the impulse rotation meter has a better performance than the paddle wheel rotation meter and the results obtained from both for the same test have a non-negligible difference. The reason for this difference is the use of relationships that relate the measured torque value to the rpm[2] based on the swirl coefficient.

Haim et al. [14] observed that in the known rotation reference calibration interface test, the results obtained from the impulse rotation meter have a large difference from the results obtained from the paddle wheel in which the rpm value is converted to equivalent torque based on the mentioned relationships.

Stone et al. [15] concluded that in measuring the amount of rotation using an impulse rotation meter and converting it to rpm based on the above relationships, the results are very different from each other, and the reverse of this theorem is also true that rpm is converted the torque is different from the results of the pulse meter. Researches generally show that the readings obtained from the paddle wheel are much smaller and different in magnitude compared to the impulse swirl meter, and this has led to the use of the impulse method being more common because it is more accurate.

In many studies, optical measurement methods (LDV) have been used to compare paddle wheels and impulse swirl meters. It was found that each type of rotation meter affects the speed axis of the rotating flow and causes a decrease in the accuracy of the measurement. Also, the comparison of the LDV method with the impulse method showed that the results obtained from the LDV method are 15% higher than the values It is the result of the impulse swirl meter method [16].

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[1] Bidirectional Recurrent Neural Network

[2] Revolutions Per Minute

Hogg et al. [17] proposed a relationship to achieve an easy method in the design of inlet ports and their ability to generate swirl flow for internal combustion engines. Using the numerical solution, he presented a relation to calculate the torque created at the end of the cylinder, based on the geometric characteristics of the inlet port and the cylinder. His method required a third of the resources and time to analyze the flow inside the cylinder compared to the experimental method. To solve the existing problem, Oqabneshin et al. [18] presented a series of relations between the measured rpm and the numerical simulation values of the torque by using the curve fitting on the graph obtained from the paddle wheel swirl meter and numerical simulation but these relationships have disadvantages such as the need for a special relationship for each point of pressure difference and flow rate, the difference in results at points of higher pressure difference, and in the design discussion, there was a need to conduct experimental tests first and then the possibility of computer simulation. This has caused that there is no suitable reference for the calibration of the swirl meter.

Mohammadebrahim et al. [19] aimed to provide a suitable prediction of tumble flow behavior and flow coefficient, through numerical simulation, a comparison was made between the measured results of the flow bench test and the predicted results of flow coefficient and tumble flow by fluent software. The simulation results show acceptable convergence with the experimental test results.

With the aim of experimentally and numerically investigating the characteristics of in-cylinder flows, Wahono [20] investigated a small engine cylinder in different valve openings using experimental tests and the CFD method. It was reported that there is a good agreement between the experimental results and steady flow simulations in terms of airflow rates, flow coefficients, and discharge coefficients at pressure drops of 300 and 600 mm H_2O.

Mohammadbrahim et al. [21] to establish a relationship between the two methods of experimental measurement of the swirl flow, including the measurement of rotational speed by a paddle wheel and the measurement of the applied moment of the swirl flow to a honeycomb geometry and the relationships that govern them, to investigate and compare these methods. The studies showed that due to the nature of the measurement method, the ratio of the swirl flow measured using the paddle wheel results in smaller numbers. Also, by conducting more tests and using appropriate conversion coefficients, the results of these two methods can be compared to each other.

This study was conducted to validate the performance of the paddle wheel swirl meter and design a method for calibrating it. First, a device with the ability to produce swirl flow was designed and built, then it was subjected to experimental testing by the steady flow bench. Next, the numerical simulation was carried out using two dynamic mesh and steady flow methods, and the simulation results were compared with the experimental test.

2- Description of the problem

In the present study, the experimental measurement and numerical simulation of the swirl flow inside the geometry of a device with the ability to produce a swirl flow will be discussed, to provide a new method for the calibration of the paddle wheel swirl meter. To create the swirl flow with the known value, a device was designed and built under the name of the calibration device. Figure 1 shows the schematic of the calibration equipment, and Table 1 also specifies the dimensions of the calibration equipment. The flow with a uniform velocity enters the cylinder tangentially from the inlet port, and due to collision with the walls of the cylinder, a pure swirl flow occurs. The net produces the actual image of the built-in calibration equipment, shown in Figure 2.

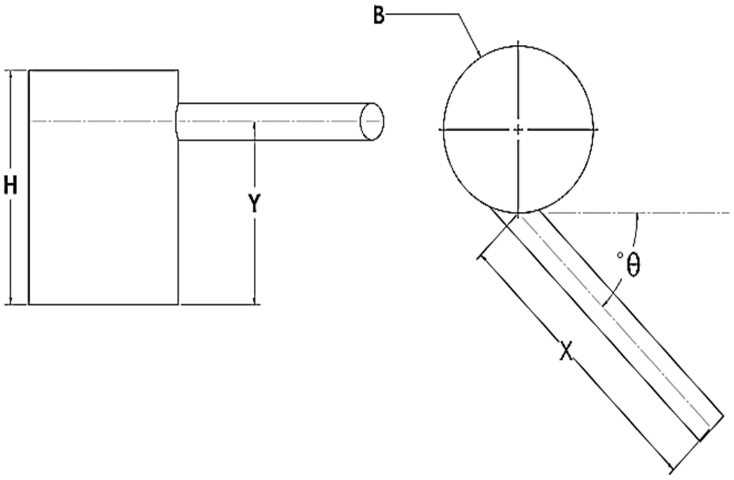


Figure 1 The General Drawing of Calibration Device

Table 1 The Geometric Dimension of Calibration Device

Characteristics	Values (Dimension)
H	115
Y	90
θ	45°
X	150
B	82

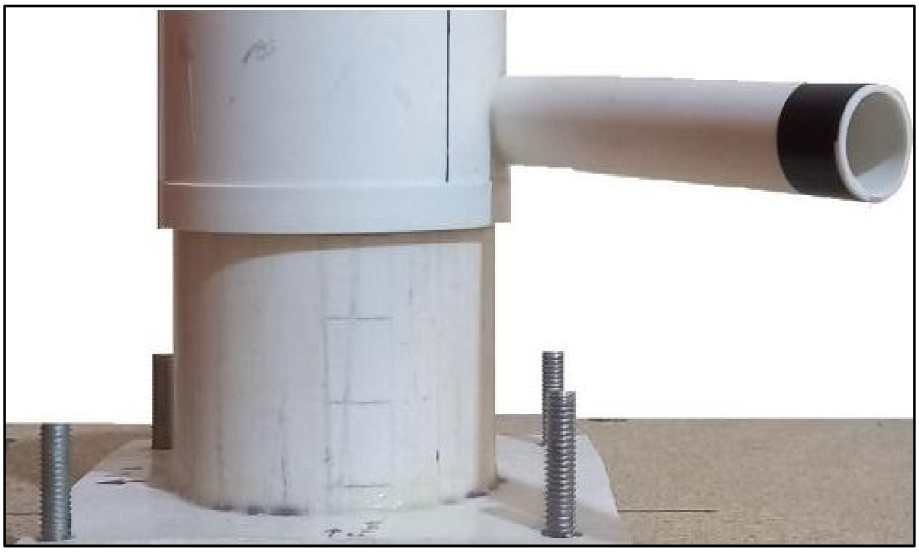


Figure 2 The image of the calibration device

3- Experimental test

The steady flow bench is a device for measuring the rotating flow inside the cylinder, the schematic of which is shown in Figure 3. The flow bench includes a flowmeter, temperature, and pressure measurement sensors, an air suction compressor, a flow analyzer, and a paddle wheel swirl meter. The beginning of the test happens with air suction by the compressor (1), the airflow enters the cylinder tangentially through the inlet port at a uniform speed and forms a swirl flow due to collision with the walls of the cylinder (2), due to the swirl flow, blade of the wheel rotates and the values of the rotational speed of the blade are measured through an optical counter sensor that is connected to the end of the shaft. The obtained rpm values are recorded during 120 seconds and at a test pressure difference of 6.5 kPa (3). After the flow passes through the flow meter, the values of the test pressure difference and air flow temperature are read and transferred to the Flow Analyzer device to calculate the density of the passing airflow (4). After that, the flow rate is calibrated by an orifice and a differential pressure sensor. The measurement is transferred to the computer by the flow analyzer device (5). The values of temperature, density, test pressure, and flow mass flow rate are recorded and collected by the computer and through the flow analyzer device (6). Table 2 shows the functional conditions of the flow bench.

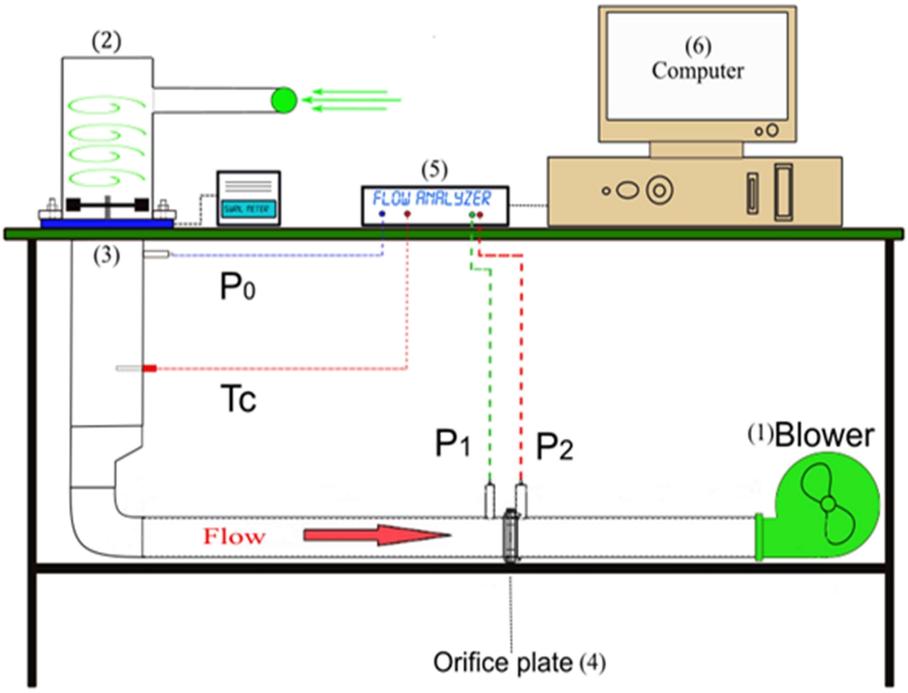


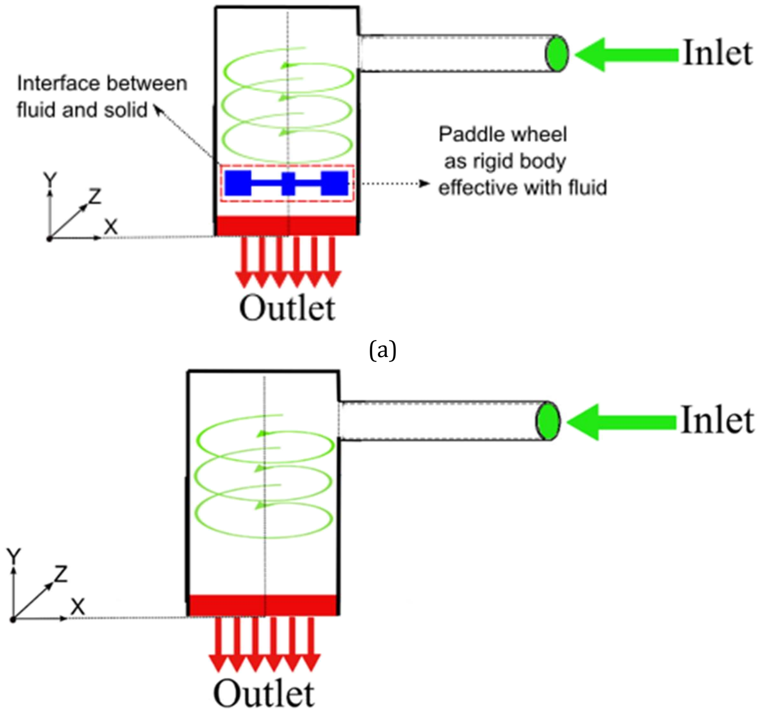
Figure 3 Schematic of the steady flow bench test

Table 2 Specifications and operating conditions of the test

Parameters	Values (or Range)
Test pressure	6.5 [kPa]
Temperature	23°C
Mass flow rate	0.0007-0.0011 [kg/s]

4- Numerical simulation

Numerical simulation can be used to further investigate the characteristics of the swirl flow inside the cylinder and reduce the costs caused by the test. In this study, the numerical simulation for the calibration equipment, as can be seen in Figure 1, was carried out by Ansys Fluent software and by two dynamic mesh and steady flow methods. Figure 4a) shows the investigated geometry for simulation by the dynamic mesh method and Figure 4b) shows the investigated geometry for the steady flow method. As it was said, the flow enters the cylinder tangentially from the border of the inlet port as a uniform flow and produces a pure swirl flow. In the first method (mesh dynamics), the flow after hitting the blade surface of the paddle wheel causes the blade to rotate and then leave the outlet boundary at the end of the cylinder surface. The value of the angular velocity of the blade resulting from the swirl flow is checked and calculated. In the second method (steady flow), the swirl flow leaves the cylinder outlet boundary without hitting any solid object, and the rotational torque value is measured and checked at the end surface of the cylinder according to the axis of rotation.



(a)

(b)

Figure 4 a) the case study for the dynamic mesh method with coordinates and boundary conditions b) the case study for the Steady Flow method with coordinates

For both methods, Velocity-inlet and Pressure-Outlet boundary conditions are considered at the inlet and the outlet, respectively. For numerical simulation using the dynamic method, the vane mesh as an effective solid body in contact with the fluid and the area around it as an ineffective interface between the fluid and solid is considered. In both methods, the boundary condition of non-slip has been applied to the cylinder walls. Table 3 shows the specifications of the flow solver for both simulation methods.

Table 3 Solver setup

Parameter	Steady State	Dynamic mesh
Time dependence	Steady	Transient
Geometry	3D	3D
Viscous model	K-ε RNG	K-ε RNG
Boundary Conditions	Velocity Inlet & Pressure Outlet	Velocity Inlet & Pressure Outlet
Algorithm	Simple	Coupled
Mesh motion	-	one DOF[1] - Rotation

5- Governing equations

In the stated problem for torque calculation based on the law of conservation of angular momentum, it can be stated that α is the angle between the normal vector dA and the velocity vector V.

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[1] Degrees of Freedom

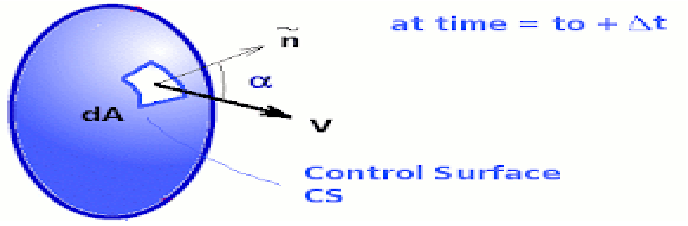


Figure 4 The Control Surface for Velocity Vector

The general state of the torque-momentum relationship is as follows:

$$M = \frac{\partial}{\partial t}\int_{CV} \rho r \times V d\forall + \int_{CS} (r \times v)(\rho v . dA) \tag{1}$$

The above relation shows the torque-momentum equation for the control volume. The term M is the torque of all the forces that enter the control volume, dA is the control surface, r is the radius of the cylinder, ρ is the density and v is the velocity. Also, in the expression on the right, the first term is the rate of change of the momentum torque inside the control volume, and the second term is the net rate of the momentum torque inside the control volume. For the two-dimensional flow in the x-y plane (Figure 6), the velocity is divided into two components: radial $v_n$and tangential v_t, and the equation is as follows:

$$T = \frac{\partial}{\partial t}\int_{CV} \rho r v_t d\forall + \int_{CS} (r v_t)(\rho v_n . dA) \tag{2}$$

For steady flow, the relationship will be as follows

$$T = \int_{CS} (r v_t)(\rho v_n . dA) \tag{3}$$

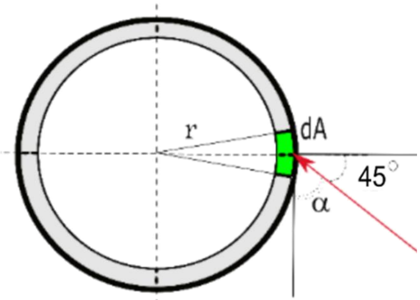


Figure 6 The Control Surface for Inlet Velocity Vector of Case Study Geometry

According to Figure 5, which shows the control surface of the input velocity vector for the mentioned geometry, relation 3 is as follows.

$$T = \int_0^r \int_0^{2\pi} r \rho V \cos \cos \theta \ \cos \cos \alpha \ V \cos \cos \theta \ r dr d\alpha \tag{4}$$

The governing parameter of swirl meter is the swirl coefficient Cs, which is a dimensionless characteristic of the rotation rate and is calculated using a paddle wheel swirl meter [20]:

$$C_s = \frac{\omega B}{V_B} \tag{5}$$

where ω is the angular speed of the paddle wheel and B is the diameter of the cylinder.

For the impulse swirl meter, the swirl coefficient is calculated from the following equation [20]:

$$C_s = \frac{8T}{\dot{m} V_B B} \tag{6}$$

where T is the torque measured by the impulse swirl meter.

According to relations (5) and (6), it is possible to convert the rotational speed of the paddle wheel into torque and vice versa (relation (7)) [20]:

$$\omega = \frac{8T}{\dot{m}V_B^2} \tag{7}$$

The main problem in the calibration of swirl meters is due to the use of relations (5) and (6), where the values of the swirl coefficient obtained from the paddle wheel and the impulse swirl meter are not the same.

6- Analysis of results

6- 1- Experimental test results

The constructed geometry in Figure 2 was examined by the flow bench. The process of conducting the test was such that every time the test was performed, the values of rotational speed at a specified flow rate and test pressure of 6.5 kPa were recorded for a period of 120 seconds and 25 repetitions. Average rotational speed values were selected for each experiment. The results obtained from the experimental test are presented in table (4) and figure (7). The values of standard deviation and standard error of the mean were calculated based on equations (8) and (9). It specifies that the process of conducting the test and its results have proper accuracy and reliability.

$$\sigma = \left[\sum_{i=1}^{n} (\omega_i - \omega_m)^2 \Big/ (n-1)\right]^{\frac{1}{2}} \tag{8}$$

$$SE(\omega_m) = \frac{\sigma}{\sqrt{n}} \tag{9}$$

Table 4 The Results of Experimental Test

$\dot{m}$(kg/s)	ω_m(rad/s)	σ	SE (ω_m)
0.0006295	70	1.491	0.298
0.0007678	85	2.533	0.506
0.0008402	93	1.514	0.3028
0.0009503	105	3.287	0.65
0.001075	119	1.4	0.28

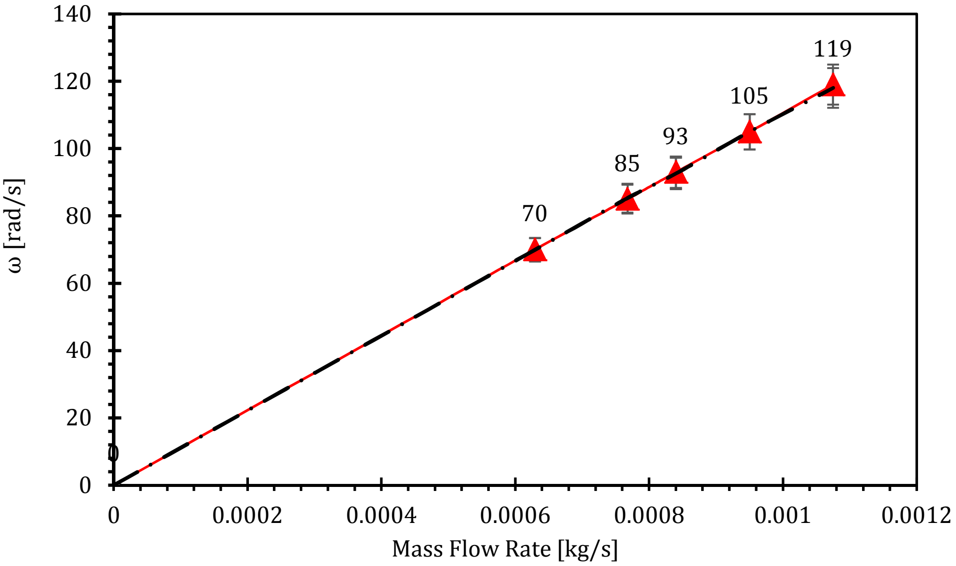


Figure 7 The angular velocity resulted from the present experimental work

6-2- Simulation results

Figure 8 shows the results of the simulation using the dynamic-mesh method. The trend of changes shows a linear increase in angular velocity with an increase in flow rate. As can be seen, the results of the numerical solution are very similar to the values obtained from the experimental measurement of rotational speed, and with a small percentage of error (less than 4%), it simulates the performance of the paddle wheel swirl meter. Figure 9 shows the formation of the swirl and its collision with the paddle wheel. The geometry is designed in such a way that the airflow enters the cylinder tangentially and creates a swirl pattern by hitting the wall. Also, Figure 10 shows an example of the velocity contour of the rotation stages of the paddle wheel for simulation using the dynamic-mesh method, in the time step t = 0.5 s, the flow has not yet developed until time t = 0.35 s, which causes the movement It becomes a paddle wheel oscillating, but over time, the flow tends towards the swirl pattern until finally, at the time step t = 1 s, a pure swirl flow is formed and the movement of the paddle wheel is uniform and without oscillation. It was also found that pure swirl causes the maximum rotation of the blade and the paddle wheel only reacts to this type of rotating flow and other patterns do not affect it.

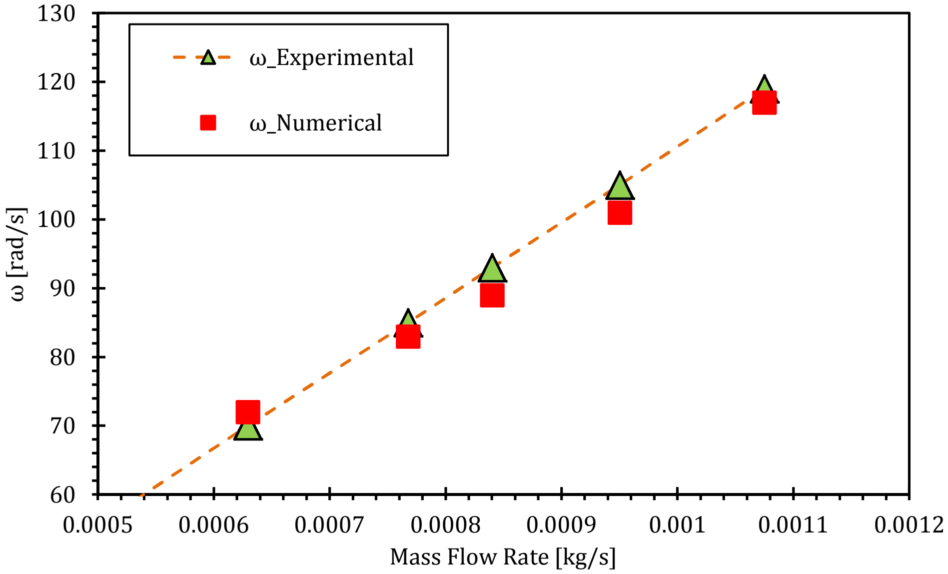


Figure 8 Results of numerical solution using dynamic mesh method compared to experimental test

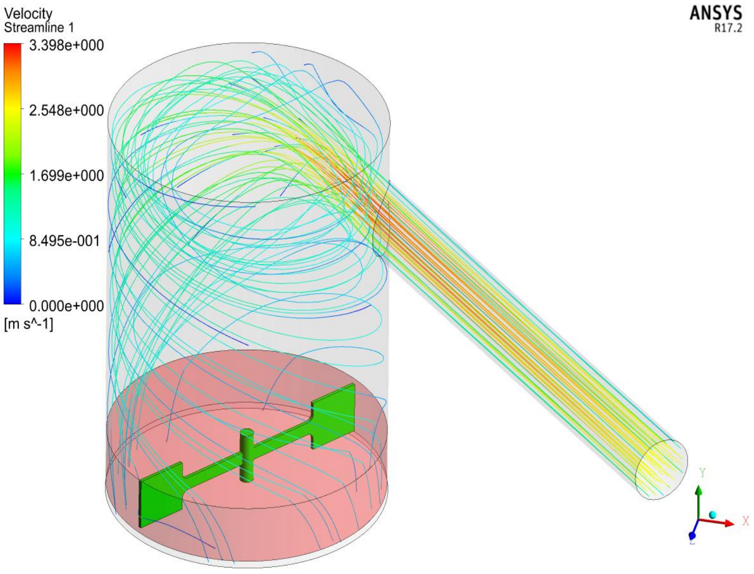


Figure 9 The velocity streamlines and swirl flow Collision with the paddle wheel

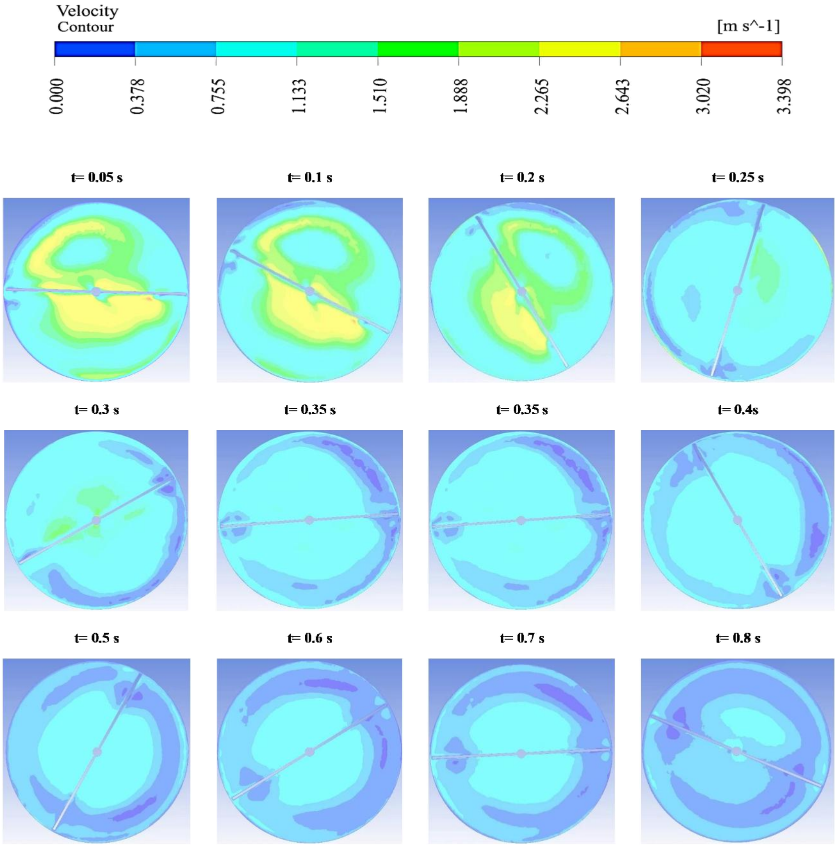


Figure 10 The Velocity contour for the dynamic mesh method (2D view)

In Figure 11, the rotational speed and torque values obtained from the dynamic grid and steady flow simulation are compared. By applying the curve-fitting to the data of this graph, a correlation between the torque produced from the rotating current and the rotational speed was obtained. Curve fitting was done using MATLAB software, and the best fit for this graph was first-order linear fitting. The correlation relationship and its constant values can be seen as Equation 10:

$$\mathrm{T} = a_0\omega + a_1, a_0 = 9.05 \times 10^{-7}, a_1 = -4.973 \times 10^{-5} \qquad (10)$$

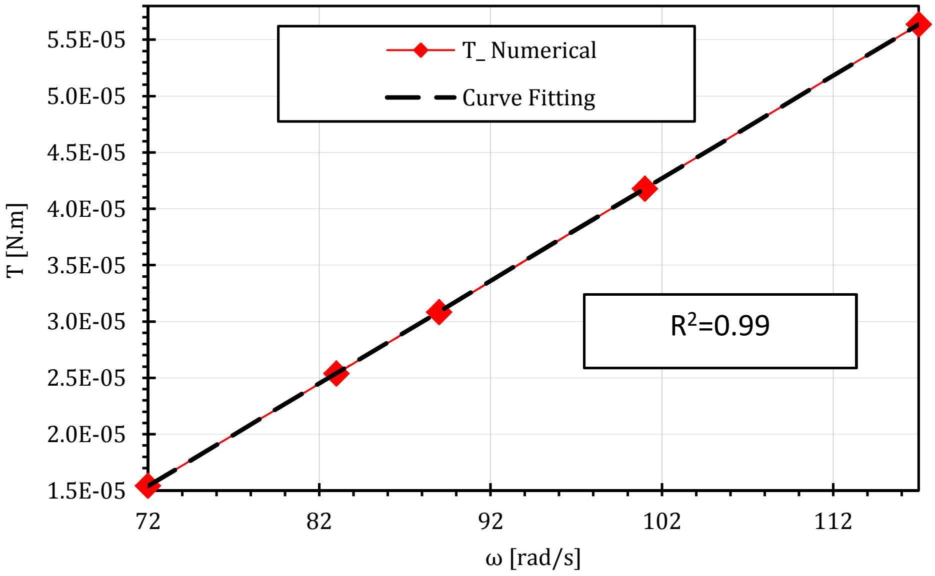


Figure 11 The curve fitting for both method Dynamic mesh and steady Flow

The torque values obtained from the steady flow method were converted to rotational speed using the correlation relationship, Figure 12 showed that the results were very close to the experimental values. It was found that the simulation using the steady flow method has good accuracy and requires much less computational cost (less than 1/48) compared to the dynamic mesh method. The resulting difference from the ideal line shows that the swirl flow has weakened along the path of the cylinder because the swirl flow pattern has been destroyed and the intensity of the swirl has decreased when it collides with the cylinder walls. This showed how much the measurement results depend on the distance of the paddle wheel from the beginning of the cylinder.

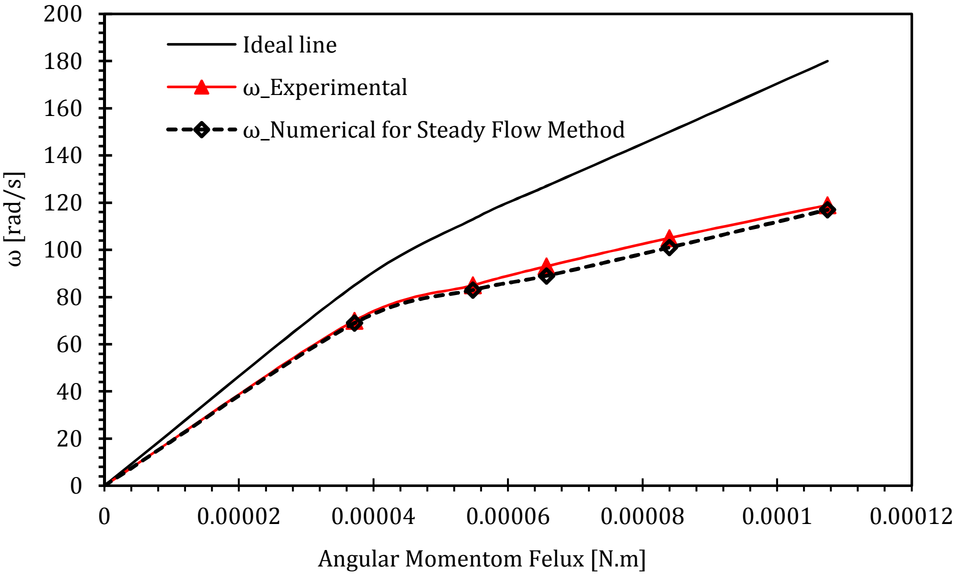
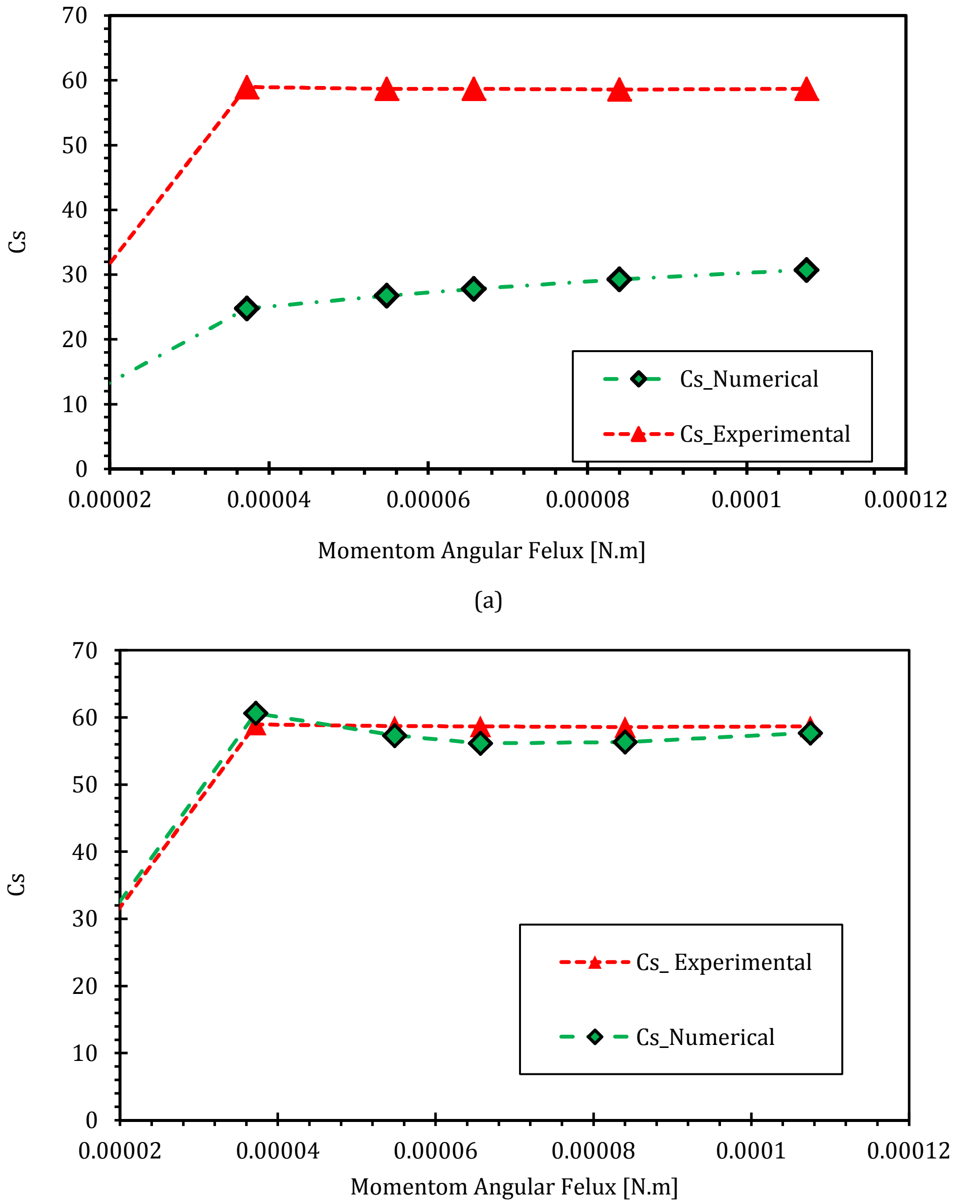


Figure 12 The Angular velocity resulted from the steady flow method compared with the ideal line and experience results

6-3- Calibration method

The main challenge in the calibration of swirl meters is when the results obtained from the paddle wheel are related to the impulse swirl meter using equation (7); Because in the conversion of angular velocity to torque or vice versa, the results obtained for the flow parameters are very far from each other and scattered, which causes the presentation of different analyzes of both types of swirl meters in the same boundary condition. Figure 13 a) shows well the dispersion and large difference of the data for the swirl coefficient obtained based on relations (5) and (6). But as it is clear in Figure 13 b), the data are very close to each other after correction due to the correlation in Table 5, and the relative error between them is less than 4%. Now, according to the obtained results, it can be claimed that a suitable and fast method has been defined and designed based on correlation and the use of calibration equipment to calibrate paddle wheel swirl meter devices.



(a)

(b)

Figure 13 a) The Cs values without correcting data b) The corrected data for Cs values by using correlation relationship

By carrying out simulation and experimental testing in a larger range of flow rates, a diagram can be provided for calibration equipment based on different flow rates and depending on the ability of the flow bench, which accelerates the calibration process of the swirl meter. Using this method, a catalog can be defined for each flow bench and swirl meter device for user use, based on which it is possible to calibrate them and ensure the accuracy of their operation. Figure 14 shows the process and steps of the paddle wheel calibration.

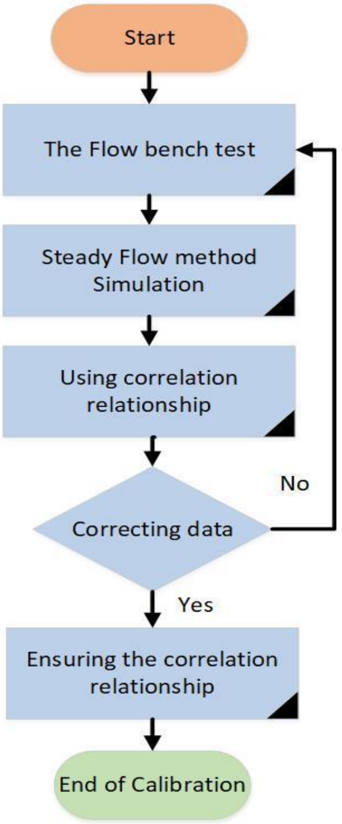


Figure 14 The calibration processes

7- Conclusion

In this research, the rotating flow inside the cylinder of a device with the ability to produce a swirl was investigated to provide a standard reference and method for the calibration of the paddle wheel swirl meter by performing experimental work and numerical simulation using two dynamic mesh and steady flow methods the results are as follows:

1- The results of the simulation performed by the dynamic mesh method are very close to the results obtained from the experimental test and have high accuracy, because it directly simulates the performance of the paddle wheel swirl meter, but on the other hand, it requires a very high computational cost.

2- The numerical solution using the steady flow method has an acceptable agreement with the experimental test results is more economical in terms of computational cost and requires a much shorter time than the dynamic grid method, but it is less accurate.

3- The measurement results are largely dependent on the distance of the paddle wheel from the beginning of the cylinder.

4- According to the results obtained from the numerical solution and experimental test, the simultaneous use of the calibration equipment along with the correlation relationship is suggested as a fast and high-precision method.

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مقاله پژوهشی

بررسی عملکرد دستگاه چرخش‌سنج پارویی با استفاده از شبیه‌سازی عددی و آزمایش تجربی

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اطلاعات مقاله

کلیدواژه‌ها:

جریان چرخشی

چرخش‌سنج چرخ پارویی

چرخش‌سنج گشتاور ضربه‌ای

میز جریان

تنظیم

چکیده

با توجه به اهمیت و تاثیر جریان‌های چرخشی داخل استوانه بر عملکرد موتورهای احتراق داخلی و تأثیر مستقیم این جریان‌ها بر کاهش مقدار انتشار گازهای گلخانه‌ای و کاهش مصرف سوخت، بررسی ویژگی‌های این جریان‌ها ضروری است. بنابراین موضوع حصول اطمینان از عملکرد دستگاه‌های چرخش‌سنج و صحت نتایج بدست آمده از اندازه‌گیری ضروری می‌شود. با توجه به عدم وجود مرجع مشخص و استاندارد و احتمال از دست رفتن عملکرد مطلوب دستگاه گرداب‌سنج در طول زمان، وجود روش و وسیله‌ای برای تأیید و تنظیم آن ضروری است. مطالعه حاضر به منظور اعتبارسنجی عملکرد دستگاه چرخش‌سنج پارویی و طراحی روشی جدید و آسان برای تنظیم آن انجام شد. نتایج شبیه‌سازی انجام شده به روش خانه‌بندی دینامیکی بسیار نزدیک به نتایج به دست آمده از آزمایش تجربی است و از دقت قوی برخوردار است، زیرا به طور مستقیم عملکرد دستگاه چرخش‌سنج پارویی را شبیه‌سازی می‌کند، اما از طرف دیگر نیاز به یک هزینه محاسباتی گران است. با توجه به نتایج به‌دست‌آمده از حل عددی و آزمایش تجربی، استفاده همزمان از تجهیزات تنظیم به همراه وابستگی همبستگی به عنوان یک روش سریع و با دقت قوی پیشنهاد می‌شود.

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