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Research Article

Development of intake manifold for student formula CMU F-914 using theoretical and simulated designs

Niti Kammuang-lue* and Worawit Borikhut

Department of Mechanical Engineering, Faculty of Engineering,
Chiang Mai University, Chiang Mai, Thailand

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Abstract - The objectives of this study were to design, develop, and construct an intake manifold for the Student Formula CMU F-914 race car, or the F-914, by using theoretical analysis together with simulation software and experimental verification of the design results. Then to compare the pressure drop in the intake manifold of the F-914, which was designed in this study, and the intake manifold of the previous race car, the F-813. The designed intake manifold consisted of an ABS restrictor with the narrowest passage located at 25% of the restrictor's length measured from the inlet, a carbon fiber surge tank with internal volume of 1,558 cm^3, aluminum elliptical profile bellmouths, and aluminum runners with a length of 102 mm. The experimental verification showed that after the pressure drop across the throttle valve was considered in the simulation, the pressure drop from the simulation was almost the same as the one from the experiment for both intake manifolds. Moreover, it was found that the intake manifold of the F-914 had lower pressure drops than those of the F-813 by 43%, 94%, 66%, 69%, and 29% at engine speeds of 6,000, 7,000, 8,000, 9,000, and 10,000 rpm, respectively. Therefore, the theoretical and simulated designs presented in this study had acceptable reliability and they could be practically used for designing the intake manifolds.

Keywords: Intake manifold, restrictor, bellmouth, surge tank, runner, student formula

1. Introduction

The Society of Automotive Engineers Thailand (TSAE) annually hosts a national racing competition for students, which is called the TSAE Auto Challenge Student Formula (Society of Automotive Engineers Thailand, 2015), to promote the students' abilities in design, research, development, and construction of various parts and equipment installed in high performance race cars, and to give opportunities for the students to use their knowledge obtained in the classroom in the field of automotive engineering to build their own practical race car. The competition and also all the race cars are restricted by the SAE Student Formula rules (2014 SAE Student Formula Rules, 2013), which are globally accepted. The competition, which has a total score of 1,000, consists of two-major events as follows: (1) dynamic events consisting of five tests as (i) acceleration event, measuring the acceleration of the race car in a straight line; (ii) skid-pad event, testing for dynamic stability of the car; (iii) autocross, evaluating the car's maneuverability and handling qualities on a tight course; (iv) endurance, evaluating the durability, reliability, strength, and overall performance of the race car and the endurance and consciousness of the driver; and (v) fuel economy event, measuring the fuel consumption of the race car during the endurance event. The total score for the dynamic events is 675. Then (2) is three static events consisting of (i) engineering design, (ii) cost report, and (iii) business presentation, for which the total score is 325. In the past, the CMU Auto Club, a student activity club in the Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, has participated in the competition every year. In the previous season, 2014-2015, the CMU Auto Club sent a race car to join the competition with the name of "Student Formula CMU F-914," as shown in Figure 1.

Figure 1. Student Formula CMU F-914.

*Corresponding Author's E-mail: niti@eng.cmu.ac.th

The primary design concepts of the Student Formula CMU F-914 (referred to as “F-914”) were lightweight components and agile movement developments and modifications on the predecessor race car —“the Student Formula CMU F-813” (F-813). The F-813 joined the competition in the previous season 2013-2014, and was focused on the downsizing of the car, such as, a decrease in all dimensions of the car, a decrease in the size of the suspension parts, wheels, and tires, and a design for a new transmission system along with a gear ratio corresponding to the smaller wheels and tires. However, the engine installed in the F-914 was the same as the one installed in the F-813, due to its power and torque suiting the size and weight of the car and the characteristic of the competition. Although the engine was identical, due to a decrease in the size and weight of a number of parts, especially in the suspension and transmission systems, the intake manifold, which was optimally designed and developed for the engine installed on the F-813, could not be used with the engine installed in the F-914 without modification. Not doing this might cause a decrease in the engine’s performance and a disagreement between the engine’s output and the changed car’s components. In light of this reason, the design, development, and construction of the intake manifold used with the engine on the F-914 were undertaken.

An intake manifold is a group of tubes or parts that is used to deliver atmospheric air to the cylinders. It generally consists of six main parts: (1) air filter, (2) throttle valve, (3) restrictor, (4) surge tank, (5) bellmouths, and (6) runners, as shown in Figure 2. Since the installed engine was a normally aspirating engine (NA-engine) — an engine without air charging devices, the performance of the engine depends on the engine’s volumetric efficiency. The efficiency subsequently depends on the mass of the air fed into the engine. In general, when the engine operates at a certain speed and load, the pistons will suck the air with a certain vacuum pressure. Therefore, if the intake manifold can be designed to have a suitable air passage, such as highly smooth wall surface, very low flow resistance, straighter tube, and minimum number of a sudden changes in cross-sectional area of the air passage, etc., the pressure drop in the air flowing into the intake manifold will be minimal. This leads to a higher mass of the air flowing into the engine that increases the engine’s performance. The methodology to design the intake manifold to have the lowest pressure drop as possible can be classified in the methods as follows: (i) theoretical analysis (Harrison, 2004; Wang, 2011); the design result is the most accurate, but the existing theories do not cover some criterions on some parts of the intake manifold, especially on the parts with more complex shapes. (ii) Empirical correlation; this method is easy and convenient although the design result is acceptably precise only when the design criteria are identical with the condition in the correlation establishment. (iii) Numerical method (Jemni, 2011; Sakowitz, 2014); the design result is reliable while the method is complicated, and the designers must be experts in mathematical problem solving. Then (iv) computer-aided simulation (Solid Works Flow Simulation, 2015); this method is now widely used according to its limited time-consumption and convenience. However, the reliability of the design result is not certain. The result should be verified before being applied to practical uses. It can be seen from the pros and cons of each design methodology that the design following the theoretical calculation simultaneously with software simulation is an outstanding design scheme because accurate results can be easily obtained while the design procedure could be finished in a short time. For this reason, the theoretical and simulating approaches were chosen for the design scheme for the intake manifold in this study. Moreover, additional experiments were conducted to verify the reliability of the design result, especially the one obtained from the simulation.

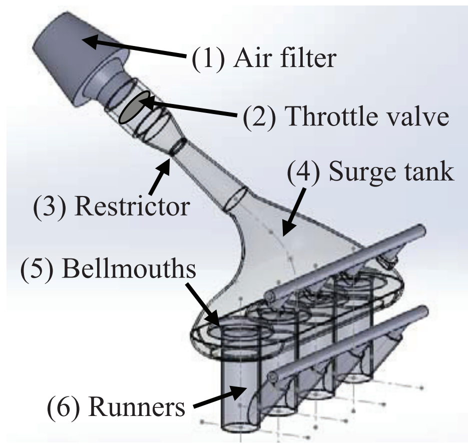


Figure 2. General components of intake manifold.

Determining the needs of the suitable intake manifold for the F-914 became a significant part of this study, of which the objectives were to design, develop, and construct the intake manifold for the F-914 using theoretical analysis together with simulation and experimental verification on the design results. Then to compare the pressure drop in the intake manifold of the F-914 to the predecessor F-813. The usefulness of this study is that a reliable, convenient, and rapid design scheme for the intake manifold was obtained. This scheme could be developed further to be used in the design of the intake manifolds installed in industrial-scale produced cars.

2. Design methodology

The target of the design of the intake manifold in this study was that the pressure drop in the air flow in the intake manifold of the F-914 was lower than that of the F-813 within the engine speed range of 7,000-9,000 rpm, which was the speed range most frequently used in the competition. The scopes of the design were as follows: (i) the intake manifold was designed for use with a 4-cylinder, 4-stroke gasoline engine (Suzuki, GSX-600R, model year 2007, 599-cm^3 displacement volume), which was installed on the F-914. (ii) The intake manifold was restricted by the 2014 SAE Student Formula rules (2014 SAE Student Formula Rules, 2013). (iii) The diameter of the restrictor located behind the throttle valve did not exceed 20 mm. Then (iv) no part of the intake manifold could be exposed throughout an outline of the frame and to the driver's cockpit. Details of the design can be described as follows.

2.1 Design of restrictor

An air restrictor is a device used to limit the width of an air channel, which does not exceed 20 mm. It is always installed between the throttle valve and the air surge tank on every race car. This is according to the competition's regulations (2014 SAE Student Formula Rules, 2013). An objective of this rule is to reduce the engine's power to a level that suits amateur drivers. The inlet diameter of the restrictor was initially defined as being equal to 38 mm, which was the same as the diameter of the throttle valve installed on the inlet of the restrictor. The length of the restrictor was initially defined as 125 mm since this length did not lead the intake manifold to be exposed out of the frame, as restricted by the rules. The theory of fluid flow could be used for the design of the restrictor. The principle of gradual contraction and expansion loss showed that the range of the suitable taper angle should be within 10^{o}-40^{o} (Fox, 2010). However, the principle did not inform the most suitable location of the narrowest cross-sectional area of the flow passage in the restrictor related to the total length of the restrictor. As when the location of the narrowest passage is changed, the ratio between the inlet and outlet taper angles of the restrictor and the pressure drop were consequently changed. Moreover, the outlet diameter of the restrictor was another parameter that affected the pressure drop across the restrictor. As some conditions of the restrictor could not be designed using the theory of fluid flow, a simulation of the air flow in various shapes of the restrictor must be conducted using the flow simulation module in the SolidWorks software (Sakowitz, 2014). The results from the simulation can be exemplified as shown in Figure 3. It can be noted from Figure 3 that the location of the narrowest passage was defined as the length percentage measured from the inlet related to the length of the restrictor.

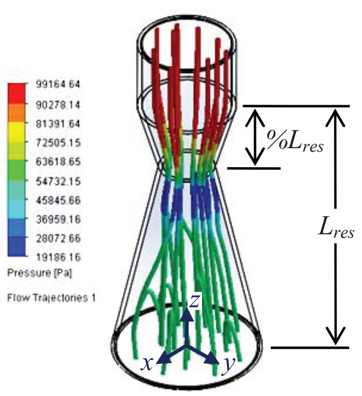


Figure 3. Simulation of air flow in restrictor.

It can be seen from the simulation that when the outlet diameter of the restrictor increased from 30 to 80 mm, the pressure drop across the restrictor continuously decreased. In addition, it was found that the optimum location of the narrowest passage of the restrictor strongly depended on the outlet diameter. When the outlet diameter increased from 30 to 80 mm, the optimum location decreased from 50% to 20%, and in turn, moved towards the inlet of the restrictor. According to the results, a restrictor with an outlet diameter of 60 mm was chosen to be constructed since this size matched with the diameter of the bellmouths (described in next topic) and the best location of the narrowest passage was at 25% of the total length.

2.2 Design of bellmouths

A bellmouth, or a bell-shape nozzle, is a device used to reduce a cross-sectional area of a fluid flow's channel between a bigger surge tank and a smaller runner. The installation of bellmouths diminishes the turbulent air flow at the inlet of the runners and consequently reduces the friction from the air flow. Since the outlet of the bellmouth has to be directly connected to a runner with the same diameter, the size of the runner should be obtained prior to designing the bellmouth. Generally, the cross-sectional area of the suitable runner should be the same as that of the engine's intake port to maintain the intake air flow's velocity as a constant. The intake port shape of the engine was almost oval with a cross-sectional area of 940.78 mm^2. The equivalent internal diameter of each runner could be found from:

$$A_r = \frac{\pi D_r^2}{4} = A_{in,p} = 940.78 \qquad (1)$$

and then, $D_r = 34.6$ mm.

An aluminum tube was chosen to be the raw material of the runner because of its smooth surface and low density (Incropera, 2002), and as 34.6-mm internal-diameter aluminum tubing is not in general markets, the closest internal diameter of the tube was alternatively selected as 36.0 mm. In light of this reason, the outlet diameter of the bellmouth was selected to be 36 mm.

Previous experimental study found that a bellmouth with an elliptical internal surface profile, as expressed in Equation (2), allowed the intake air to flow through with a higher mass flow rate than that of the airfoil profile and simple radius (Blair, 2006).

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad (2)$$

Since a is the length of the runner, which was the best value obtained from the part study (Kammuang-lue, 2012), and was 23 mm. b is the difference in the radius between the inlet and outlet of the bellmouth. As a width of the flange between the runners and the surge tank was initially defined as 70 mm, the internal diameter of the inlet of the bellmouths was 62 mm. In the case of the outlet, the internal diameter was restricted by the size of the runners, which was 36 mm. Therefore, b could be found from (62 – 36) / 2 = 13 mm. When a and b were substituted into Equation (2), the elliptical equation describing the profile of the bellmouth in this study equaled to obtain as Equation (3). The shape of the designed bellmouth is shown in Figure 4.

$$\frac{x^2}{23^2}+\frac{y^2}{13^2}=1 \quad (3)$$

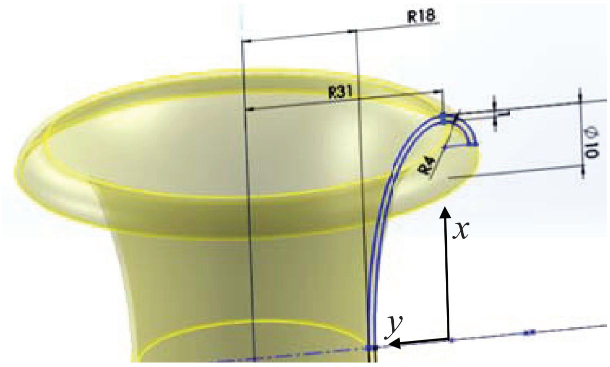


Figure 4. Designed bellmouth.

2.3 Design of surge tank

An air surge tank is an empty chamber used to reserve sufficient intake air for combustion. The suitable surge tank must have enough capacity to continuously distribute intake air to each cylinder. The volume of a surge tank can be determined using the Helmholtz resonator model (Heisler, 1995), expressed as:

$$f_R=\frac{C}{2\pi}\sqrt{\frac{A_t}{L\,V_R}} \quad (4)$$

Where f_R is the resonant frequency of the effective engine speed, which was defined as 7,000 / 60 Hz. C is the velocity of sound in air, which is 350 m/s. A_t and L_t are the cross-sectional area and the length of the tuned pipe — the portion of the intake manifold between the throttle valve and the inlet of the surge tank, respectively. V_R is the resonating volume or the internal volume of the whole intake manifold. Since the cross-sectional area of the restrictor was not uniform, A_t in the previous equation was substituted by an average cross-section area, which could be found from:

$$A_{t,avg}=\frac{V_t}{L_t} \quad (5)$$

When Equation (4) was substituted with Equation (5) and with all the above defined constants, the resonating volume was achieved as:

$$f_R=\frac{C}{2\pi}\sqrt{\frac{V_t}{L_t^2V_R}} \quad (6)$$

$$\frac{7{,}000}{60}=\frac{350}{2\pi}\sqrt{\frac{148.931\times10^{-6}}{\left(12.5\times10^{-2}\right)^2V_R}}$$

$$V_R=2{,}172.94\times10^{-6}\ \text{m}^3=2{,}172.94\ \text{cm}^3$$

The resonating volume was the internal volume of the air flow channel from the throttle valve to the intake valve's face, which consisted of the volume of the surge tank, all the bellmouths, and the runners. The volume of the surge tank can be found using Equation (7). The length of each runner was initially defined to be 102 mm, which was the longest length for the intake manifold that could fit in the race car.

$$\begin{aligned}V_s&=V_R-V_b-V_r\\ V_s&=2{,}172.94\times10^{-6}-(4\times50\times10^{-6})-\left[4\times(\pi\times1.8^2\times10.2)\times10^{-6}\right]\\ V_s&=1{,}557.65\times10^{-6}\ \text{m}^3=1{,}557.65\ \text{cm}^3\end{aligned} \quad (7)$$

2.4 Simulation of intake manifold

It can be seen from the above design that the exact shape and dimensions of the restrictor, bellmouths, and runners were completely obtained, except for the surge tank of which only the suitable volume was determined, but the suitable shape was still in a black box. From this point, eight possible shapes of the surge tank were created in this study with the same internal volume of about 1,558 cm^3. Then, each shape was modeled in the simulation software and connected to the restrictor, bellmouths, and runners to be the modeled intake manifold. Consequently, the air flow in each of the modeled intake manifolds was simulated to find the pressure drop and streamline. The pressure at the outlet of the runners was initially set to 50 kPa, which was an average pressure due to the suction of the engine at an engine speed about 7,000 rpm. The atmospheric pressure of the surrounding air before entering the restrictor was defined as 101.325 kPa. The pressure drop along each modeled intake manifold was recorded as shown in Table 1. It can be seen that the intake manifold model No. 1 caused the lowest pressure drop. Therefore, this optimized shape of the surge tank and intake manifold was chosen to be constructed and installed on the F-914 for further experiments. It should be noted that although an error in the pressure drop obtained from the simulation could be observed in each of the modeled intake manifolds, the magnitudes of the errors were nearly the same and were less than 2%. Therefore, the errors could be reasonably neglected from consideration when selecting the optimized shape of the surge tank and intake manifold.

3. Experimental setup and procedure

The optimized intake manifold for the F-914 was constructed to have the same shape and dimensions as in the design and simulation results. It consisted of the restrictor, which was extruded by a 3D printer with the raw material of acrylonitrile butadiene styrene (ABS), which is a thermoplastic. The surge tank was shaped from carbon fiber reinforced with aluminum plate for strength. The bellmouths were machined from an aluminum block by a CNC machine. The profile of the internal diameter of the bellmouth was the same as in the elliptical equation, from above. The runners were made of an aluminum tube. One end was welded to the outlet of the bellmouth and the bottom plate of the surge tank and another end was welded to the flange made of an aluminum plate machined to have four holes with the same shape as the intake port of the engine. All components were attached together to form the complete intake manifold. High-temperature sealant was applied to all the fittings to prevent any leakage. Finally, the intake manifold was installed onto the engine as shown in Figure 5.

Table 1. Modeled intake manifold and pressure drop.

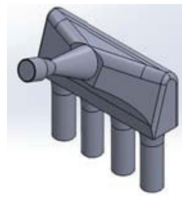
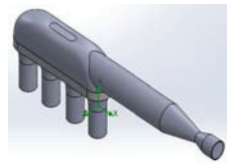
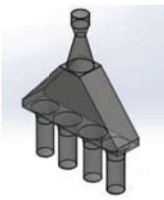
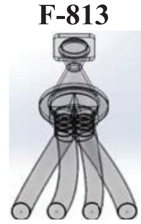
Modeled intake manifold	Pressure drop (Pa)	Modeled intake manifold	Pressure drop (Pa)	Modeled intake manifold	Pressure drop (Pa)
No. 1 	**48,546**	No. 4 	48,650	No. 7 	48,760
No. 2 	48,622	No. 5 	48,701	No. 8 	48,569
No. 3 	48,630	No. 6 	48,760	**F-813** 	**50,534**

Figure 5. Complete intake manifold for the F-914.

The experimental investigation of the pressure drop across the intake manifold was conducted by installing a manometer into the inlet of the restrictor and the outlet of each runner. Moreover, vacuum gauges were installed into the inlet of the restrictor and the outlet of each runner to measure the local pressure.

The investigation was divided into two parts. (i) Verification of the pressure drop obtained from the simulation, in which the experimental procedure was started after the engine was hot started and accelerated until the local pressure at the runner was 50 kPa. Then, the difference in head of the water inside the manometer was measured and used to determine the pressure drop with Equation (8). The intake manifold of the F-813 was substituted and tested with an identical procedure to find the pressure drop. Finally, the pressure drop of each intake manifold obtained from the experiment was compared to the one obtained from the simulation to verify the reliability of the simulation. (ii) Comparison of the pressure drop in the intake manifolds between the F-914 and the F-813, in which the experimental procedure was the same as in the first part except that the engine was accelerated until the speed was equal to 6,000, 7,000, 8,000, 9,000, and 10,000 rpm without any restriction in the local pressure at the runner. The pressure drop at a certain engine speed was then measured and calculated. The pressure drops obtained from the F-914 and the F-813 intake manifolds were finally compared.

$$\Delta P = \rho g \Delta h \quad (8)$$

4. Results and Discussion

4.1 Verification of pressure drop obtained from simulation

It could be seen from the pressure drop obtained from the experiment and simulation, as shown in Table 2, that the pressure drop from the simulation differed from the one from the experiment for both intake manifolds. This was because the pressure drop across the throttle valve was not considered in the simulation. On the contrary to the actual experiment, the throttle valve must be installed onto the intake manifold for controlling the engine speed. Therefore, if the pressure drop across the throttle valve was taken into account and the simulation was conducted again, the pressure drop from the simulation would be closer to the one from the experiment for both intake manifolds. The percentage difference between the pressure drops obtained from the experiment and simulation could be reduced to 7.17% and 13.73% for the intake manifolds of the F-914 and F-813, respectively. From this it can be concluded that the design results obtained from the simulation had acceptable reliability and the method could possibly be used as the scheme for designing the intake manifold.

Table 2. Pressure drop obtained from experiment and simulation for both intake manifolds.

Pressure drop	Intake manifold	
	F-914	F-813
(i) Experiment (Pa)	2,241	2,435
(ii) Simulation, without throttle valve (Pa)	48,546	49,571
(ii) – (i) Difference (%)	2,066.51	1,936.18
(iii) Simulation,with throttle valve (Pa)	2,080	2,100
(iii) – (i) Difference (%)	7.17	13.73

4.2 Comparison of pressure drop in intake manifold between F-914 and F-813

It could be seen from the comparison of the pressure drop in both intake manifolds that the intake manifold of the F-914 had a lower pressure drop than the intake manifold of the F-813 of 43%, 94%, 66%, 69%, and 29% at the engine speeds of 6,000, 7,000, 8,000, 9,000, and 10,000 rpm, respectively, as shown in Figure 6. Moreover, it could be seen that when the engine speed was 7,000 rpm, the intake manifold of the F-914 had the lowest pressure drop of 87.5 Pa, which was due to this being the speed used in the design following the Helmholtz resonator model. It can be concluded that the design and development of the intake manifold for the F-914 could significantly increase the performance of the air delivered to the engine installed on the Student Formula CMU F-914. Although, there was no evaluation of the power and torque obtained from the engine with each intake manifold, due to limited instruments, the competition results in the acceleration event could be directly deduced for the engine's performance. It was found that the Student Formula CMU F-914 took 4.35 s to cover the 75-m drag strip, while the Student Formula CMU F-813 took a longer time of 5.04 s. This can practically verify that the design and development of the intake manifold in this study increased the overall engine's performance and subsequently decreased the time in the acceleration event by 0.69 s, or 13.69%.

5. Conclusions

The intake manifold for the Student Formula CMU F-914 has been thoroughly designed, developed, and constructed in this study using theoretical analysis together with simulation software and experimental verification of the design results. The designed intake manifold consisted of an ABS restrictor with the narrowest passage located at 25% of the restrictor's length measured from the inlet, a carbon fiber surge tank with an internal volume of 1,558 cm^3, aluminum elliptical profile bellmouths, and aluminum runners with the length of 102 mm. The experimental verification showed that the pressure drop from the simulation obviously differed from the one from the experiment for both intake manifolds since the pressure drop across the throttle valve was not included in the simulation; however, after the pressure drop across the throttle valve was considered in the simulation, the pressure drop from the simulation was almost the same as the one from the experiment. Moreover, it was found that the intake manifold of the F-914 had a lower pressure drop than that of the F-813 at every engine speed. The practical outcome from the design and development of the intake manifold was a lower elapsed time in the acceleration event of 0.69 s, or 13.69%.

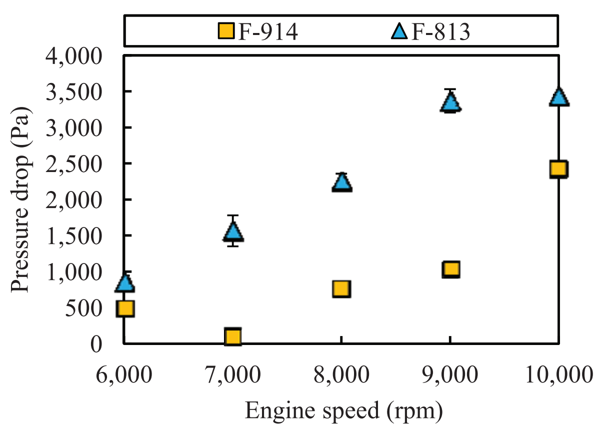


Figure 6. Pressure drop in both intake manifolds.

6. Nomenclature

$A_{in,p}$ Cross-sectional area of an intake port, mm^2
A_r Cross-sectional area of a runner, mm^2
A_t Cross-sectional area of a tuned pipe, m^2
D_r Inside diameter of a runner, mm
C Velocity of sound, m/s
f_R Resonant frequency, Hz
Δh Head difference, m
L_{res} Length of a restrictor, m
L_t Length of a tuned pipe, m
ΔP Pressure drop, Pa
V_b Bellmouth volume, m^3
V_R Resonating volume, m^3
V_r Runner volume, m^3
V_s Surge tank volume, m^3
V_t Tuned pipe volume, m^3
x Length of a bellmouth, mm
y Different radius between inlet and outlet of a bellmouth, mm
ρ Density of water in manometer, kg/m^3

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