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Gas Core Reactor

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I. Executive Summary

Our team was tasked to design a sampling system that transports the exhaust of a diesel engine directly into the already existing testing station of Southwest Research Institute (SwRI). The final prototype meets nearly all the objectives stated in the initial project plan, with the exception of the temperature requirements. The team experienced a delay in the arrival of the heated pump; therefore, the prototype was tested with an alternative pump that works similarly to the one ordered. This solution proved successful and allowed for most of the planned tests to be conducted. This pump allowed the team to prove that our design functions as expected with no major problems. Although further testing is required upon arrival of the heated pump, the basic objectives of the design have been met. These objectives were the creation of a portable cart, 50 L/min flow, and proper control of the flow through the different paths in the piping system as well as low overall pressure.

The prototype was subjected to a leakage test, pulsations test, and a flow test. The leakage test was successful around the operating flow rates but failed at higher pressures, due to back pressure which forced delicate connections with the glass tubing to move out of place. However, the system is not designed to undergo the extreme pressures we tested it with, so it can be concluded that the system will be free of any leakage under the required conditions. The pulsations tests successfully showed dampening in the flow as the flow meter read consistent values with little fluctuation, ranging by about ± 0.35 L/min. Lastly, the whole system was tested under different flow rates and the valves were proportionally varied to determine their sensitivity and their ability to control the flow as desired. The results demonstrate that the valves functioned as expected, although they are unresponsive until they are at least 25% open.

II. INTRODUCTION

Catalytic converters have been part of the automotive industry for years and they play a very important role in combating global warming. Catalytic converters function as packed bed (This statement is incorrect. The catalysts are monoliths and not packed bed.) reactors, which remove harmful hydrocarbons and toxic gasses such as carbon monoxide (CO) and oxides of nitrogen (NOx). In order to maintain the development of catalytic converters and thus produce environmentally friendly vehicles, it is necessary to be able to test engine and catalytic converter together under real world conditions. Currently, SwRI performs tests on different catalytic converters by re-creating the gasses present in an engines exhaust gas with the use of the basic elements like carbon, hydrogen, and nitrogen. This is inefficient since real exhaust gasses have hundreds of hydrocarbons and particulate matter that cannot be simulated accurately. Our task is to create a portable system that allows SwRI engineers to test real engine exhaust gas directly. Our system must be able to collect exhaust gas and transport it through a catalytic converter core for testing. Our system will allow for testing of various engines to determine if they meet emissions standards and will also allow for testing of different catalytic converter designs. Our design must be capable of achieving a number of constraints. These are; generate a 50 L/min flow, maintain gas temperature at 191 degrees C throughout the testing, and maintaining a low overall pressure. The ultimate requirement is to be able to maintain the composition of the exhaust gas. Additionally, the design must be able to easily sample the gas from any exhaust pipe, it must filter out any particulate present in the gas, and it must allow for Fourier Transform Infrared (FTIR) testing before and after the gas is treated by the catalytic converter. This report will evaluate the designs capability to generate and manipulate a 50 L/min flow throughout all areas of the design with no leakage. It will evaluate the proper functioning of each valve, correct measurement of the flow meter, and proper pressure throughout the system.

III. OVERVIEW OF THE DESIGN AS TESTED

To maintain the accuracy of results, the most important factor is that the design is able to maintain the composition of flowing exhaust gas throughout the pipe lines. The sample can be taken either directly from a car, or a designated engine room. The sample is then directed through a heated filter to remove undesired particulate matter. Then, the sample travels through a heated pump which then delivers the gas to a furnace, containing the catalytic core. The gas can then be tested by the FTIR system for composition analysis before and after the furnace. The design is portable and can be rolled through doors and the SwRI lab with ease.

The main components included in the design are a pump, a heated filter, a furnace and glass tube, a flow meter, and control valves. A heated diaphragm pump was ordered to pull the exhaust sample from the test engine and supply this sample to the catalyst sample to be tested. Due to long lead times with the delivery of this pump, the team and sponsor decided to use a similar, but slightly smaller, pump for the initial testing process. The alternative pump proved to be sufficient to create up to 40 L/min flow, while also providing the pulsations we would expect from the heated pump. This allowed the team to test how effective the design is at reducing pulsations while providing confidence that it will behave similarly when the heated pump is installed. Since this pump used for testing does not have a heating feature and cannot handle 191 ℃, the team had to delay temperature testing until the heated pump arrives. When it arrives, we would suggest re-testing the design for pulsations and flow control, as well as conducting the temperature test outlined in the test plan document. Pulsation dampening, flow control, and pressure test results for future tests should be similar to the ones already performed.

The heated filter is manufactured by Corning DuraTrap, and serves to remove particulate from the exhaust system. This is primarily done to avoid buildup of soot in the pump and ensure a clean stream through the furnace. The Corning DuraTrap filter has a low pressure drop and is made up of Aluminum Titanate, a ceramic material designed to withstand high temperatures with a high thermal shock resistance. The high thermal shock resistance and the low pressure drop serves to our interest as our system functions at high temperatures and requires a low overall pressure drop.

The Micro-Motion Coriolis Flow meter manufactured by Emerson is used in this prototype to measure the flow rate entering the furnace. Unlike many flow meters that measure volumetric flow, a Coriolis flow meter measures mass flow rate which is not a function of temperature or pressure. This allows for accurate readings, no matter the operating conditions. Additionally, many flow meters have moving parts embedded within them, which requires regular maintenance. A Coriolis flow meter on the other hand, has no moving parts resulting in minimal maintenance cost after the initial purchase. Furthermore, the Emerson Micro-Motion flow meter comes equipped with additional sensors that can measure temperature, density, and volume. In conjunction with the transmitter that comes with the sensor, the user can read all desired parameters in different units. Finally, this flow meter can withstand temperatures of 210 ℃, which is well within the upper limit of 191 ℃, the operating temperature of the system.

The furnace that met our requirements was manufactured from a company by the name of ThermoFisher Scientific. The objective of our project is to guarantee a temperature of 191 degree C to ensure that the exhaust gases will remain inert. Design elements of the furnace such as the double-shell construction and variable density insulation enhances performance. The Thermo Scientific Tube Furnace has a temperature capability of up to 1200 degrees C which is well within the ability of obtaining our temperature requirement. Additionally, this furnace is equipped with energy-efficient heating elements that provide superior temperature uniformity, fast heat-up and cool down and require little or no maintenance. For added safety, the heat-reflecting, element support assembly creates two highly effective insulating air spaces and the unique cabinet design helps keep the exterior surface temperature low.

Other than the components described above, several connections and valves were utilized to put the system together. These connections are listed below,

- Proportional valves to provide control over the flow of the system. In total, 2 control valves were used. One them controls the flow to the bypass, and the other controls the flow to the furnace. Both can function together to provide the desired flow rate of 50 L/min through the furnace.

- The two proportional valves are used to provide control over the flow of the gas through the system. One valve is used to control the flow towards the furnace, while the other is used to control the flow towards the bypass line. Using both valves in conjunction, multiple flow rates can be achieved from zero to 50 L/min. There is one 3-way valve which will be connected to the FTIR sampling system. The valve allows for the FTIR to sample gas from the inlet or outlet of the furnace. Various fittings and junctions were used. All of them are Swagelok products. There are various inline 3/8'' connecters as well as two T-connections. Additionally, there are two ½'' – 3/8'' converters for the assembly of the flow meter. Additionally, there is one 5/8'– 3/8'' converter at the end of the quartz tube.

The current design provides space for the addition of heated tape and heated pump once these components become available. Additionally, the sample line and probe were not included since various sample lines are present in SwRI labs. Our design will connect to and work with these sample lines once the final components have arrived. Overall, the prototype as tested suggests that the results outlined below will be similar to future tests involving the heated pump, as this represents only a minor adaptation from the current design.

IV. PROTOTYPE TESTS

Three distinct tests were conducted on our design to determine its ability to achieve the original goals.

1. Leakage

Overview: To ensure that the system is free of any leakage

Objectives: Our design utilizes many fittings and different connections between components. As a result, leakage at any given connection is a possibility that we need to address. Therefore, the goal of this test to check whether the system is free of leakage. The test was conducted by subjecting the design to high pressures in order to determine if there is leakage at any point.

Features evaluated: Fittings, connections, junctions, and valves

Test scope: To check for leakage at various flow rates under standard conditions. This test will not be done at 191 C as it is safe to assume that leakage is not a function of temperature. The test was done with the alternate pump to create high pressure/ We restricted the sampling system's outlet to generate high pressure and test for leakages

Test plan:

a. Materials:

1. A gas sampling station

2. Mass flow meter
3. Skeleton of our tubing system

Acceptance criteria: This test ensures that whatever enters the system, safely exits it, therefore proving that the proposed solution is free of any leakage. Since our sponsor will be testing the exhaust of an engine, it is paramount that no leaks occur as any form of leakage will be detrimental for the workspace.

Results: High pressure testing was successful in identifying 2 leaks in the sampling system. These were related to certain junctions where the fittings had not been tightened completely. As we increased pressure to identify more leaks, the sealing junction that holds the quartz tube began to fail. Meaning that the pressure was too high for the junction to hold the tube in place. At this point we stopped the testing and concluded that the system will not experience any leakage under normal operating conditions. These pressures were much higher than the design specifications for the system, so the system was assumed to perform within acceptable tolerances.

2. Pulsations

Overview: This test will ensure that the system is free of any major pulsations, and whether our proposed solution for dampening works effectively.

Objectives: Our design utilizes a diaphragm pump which introduces substantial pulsations in the system. Since our goal is replicate the action of a real engine exhaust, it is important to dampen the pulsations before they reach the furnace. Since pulsations dampen over time, our solution is to increase the distance between the pump and the furnace. Therefore, our test will show whether increasing the distance significantly dampens the flow.

Features evaluated: Pulsations created by the pump

Test scope: To check whether our solution sufficiently dampens the pulsations. Furthermore, a critical length needs to be determined which sufficiently dampens out the pulsations. For this, pulsations will be checked at various lengths ranging from 1 - 5 feet.

Test plan:

a. Materials:

1. A diaphragm pump
2. Tubing of various lengths
3. Pressure gauge
4. Fittings

b. Technique: For this test we will utilize a pressure gauge at the inlet of the furnace. To check whether pulsations are sufficiently dampened, we will check for fluctuations in the pressure reading.
c. A table will be constructed that will list the pressure reading and the corresponding fluctuation in the reading at various lengths. The length at which fluctuations are minimum will be the critical length that is needed to dampen pulsations.

Acceptance criteria: Our sponsor requires a steady flow, free of major pulsations. Our test will determine the appropriate length of tubing required to dampen pulsations before they reach the furnace.

Results: Our initial tests indicated that 2 feet is more than enough tubing to dampen the pulsations to a minimum acceptable level. We also discovered that the flow meter itself acts as a pulsation dampener. The persistent pulsations were measured by setting the pump to create the maximum flow possible (40 L/min) and measuring the minimum and maximum readings from the flow meter. We found that the pulsations according to the flow meter were ± 0.34 L/min. The pulsations at the outlet of the piping system are negligible. It was discovered that the flow meter dampens pulsations by observing the outlet of the system. When the pumps flow is directed only through the flow meter, we find that there are no pulsations at the outlet of the system. When all the flow is directed through the bypass line, we find that there are significantly stronger pulsations at the outlet. However, this is not a problem since pulsations present in the bypass line will not affect any aspect of the tests to be performed by SwRI. The pulsation testing was conducted at 40 L/min, although slightly below our initial requirement, we believe the design dampens pulsations sufficiently so that this will not be a problem once the final pump is installed.

3. Pump performance
Overview: To ensure that the pump is able to deliver the desired flow rate to the furnace.

Objectives: To test the pump with a constant flow and vary system configurations to determine proper control of flow through the system. Furnace and bypass line valves will be set at different positions to determine the effects of this on the pump performance and behavior.

Features evaluated: The main feature evaluated is if the pump can indeed deliver 50 L/min to the furnace line, regardless of how much flow is diverted to the bypass line. This test will also determine the complete range of flows that can be directed to the furnace.

Test scope: The conditions of the test must be that the whole system is completed and operational with the leakage and pulsations test completed. The temperature and pressure tests do not need to be completed before testing pump performance because it is necessary to ensure proper pump operation to successfully test temperature and pressure variables. This test will involve keeping the pump at a constant flow while varying the position of the control valves. The valves will allow for more or less flow to be directed to the furnace while discarding the rest of the gas through the bypass line. This method will allow for varying gas flow velocities through the furnace section. The testing will involve all different valve positions to determine if and how the configurations affect the behavior of the pump and flow throughout the rest of the system.

Test plan:

a. Materials:

1. Completed piping system
2. Heated diaphragm pump
3. Pressure transducers
4. Flow meter

b. Technique: We will need to be able to accurately read and control the flow meter to ensure accuracy in our testing. Familiarity with the pump workings is also required.

c. The data collected will be in the type of qualitative observations and quantitative data regarding flow. This test will allow us to determine what are the minimum and maximum flow rates that can be directed through the furnace by only manipulating valve positions and keeping the pumps operation at a constant flow. It is important for us to determine this range in order for SwRI to know the limits of the system we deliver.

Acceptance criteria: The test will be considered successful if a flow rate of 50 L/min is achieved in the furnace section with the possibility of at least ±10 L/min. The pump will consistently deliver 50 L/min flow or more through the sample line. Then the system will divide the total flow in order to obtain around 50 L/min going into the furnace, while the rest is discharged safely through the bypass line.

Results: Since this test was conducted with the alternate pump, the team was not able to achieve exactly 50 L/min flow. The maximum flow recorded with the pump was of 40 L/min. Therefore, we decided to use pressurized air flow from the control's lab here at Trinity University in order to conduct testing of flow at the 50 L/min level. This was done in order to ensure our design would work properly at 50 L/min. We tested the mechanics of the sampling system and its control valves by conducting 4 different tests. These were set with a flow of 30, 40, 50, and 60 L/min, as measured by our flow meter. All valve positions were tested in order to determine the sensitivity of the control valves. We found that our proportional valves don't respond until they are at least 25 % open. After this point, the control for flow is very accurate and can be set with an accuracy of 1 L/min. We tested all valve positions to determine the limitations of the system and found that the control of flow is highly accurate. Our final test involved using the pulsating flow provided by the alternate pump to simulate pulsations that would be present in the final iteration of the prototype. The system performed successfully and provided accurate control for the flow that enters the furnace. One slight problem that we found during our testing is that the 3-way valve that controls the FTIR feed is subject to a slight amount of flow when opened. This problem is minimal and does not affect the overall operation of the system or the accuracy of the flow measurements at the furnace inlet. The results table for our testing can be seen in Appendix D.

V. CONCLUSIONS

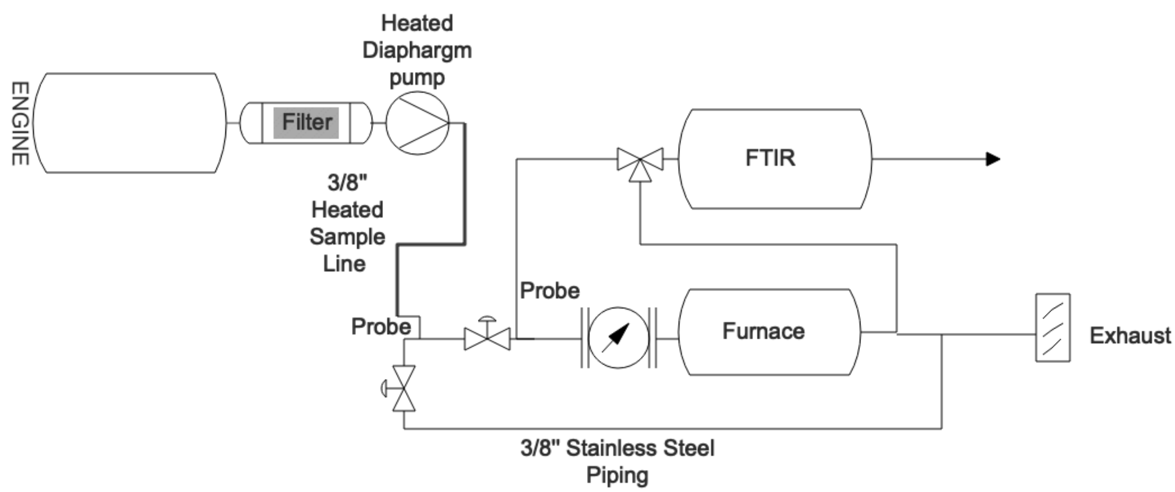
The design as tested was able to meet most of the objective outlined for this project. The prototype does not currently have the capabilities to maintain the gas at 191 degrees C, but it does meet all other requirements. Even though the design was tested with the use of an alternate pump, our team was able to provide an alternative solution in order to prove that the design is able to handle a 50 L/min flow rate with minor fluctuations of +/- 1 L/min accuracy. Additionally, pulsations will not be an issue with the final iteration as our Emerson Micro Motion Coriolis flow meter does a great job at dampening pulsations. Furthermore, the current design and location of our components are readily available for the installation of the new pump when it arrives as it will replace our alternate pump. We believe the results achieved throughout this testing process will hold true in future testing and will carry forward with SwRI's original specifications.

Three tests were conducted and results for each test (Leakage, Pulsations, Alternate Pump Performance) were as follows; for leakage testing our group was able to identify and resolve all leakage issues. We have made the conclusion that under standard operation our system is leakage-free and will accurately contain all gases. The next test involved checking for smooth, steady flow. Our pulsations test proved to be successful as the Coriolis flow meter does a great job of counteracting pulsations, ensuring an accurate flow measurement and negligible pulsations at the outlet of our system. Lastly, the pump's performance was tested and found to be successful at several different flow rates and valve openings. Since our current pump was not able to produce exactly 50 L/min flow, we modified our testing and used another source of pressurized air in order to test 50 L/min and above. This modification proved that the piping system was able to accurately manage and control 50 L/min with no further complications. The test was also conducted by using the current alternate pump, which was only able to provide 40 L/min, but the results for this test were very similar to the results obtained from using pressurized air. Therefore, we can conclude that the system operates exactly as expected.

Overall, this prototype has proven itself to be highly successful in achieving a system that is free of any leakage under standard operating conditions, while dampening pulsations to ensure a smooth flow of gas. The team acknowledges that work remains to be done regarding the temperature requirement as we test out our furnace but is confident that the results obtained during the testing process will hold true for any future testing. However, we would recommend to re-test flow control and pulsations upon arrival of the heated pump, to ensure that our current results indeed hold true under the original specifications given by SwRI. Lastly, our team will perform temperature testing to ensure the proper handling of inert exhaust gas throughout the entire system.

VI. Appendices

Appendix A: P&ID diagram



Appendix B: Instructions for use (Operating Manual)

Our piping system consists of a total of two proportional valves, one 3-way valve, an electronic flow meter, furnace, filter, and a pump.

The operation of the pump is simple as it just involves connecting it to a power supply. It has no control over its operating speed and strength. The filter is heated and should work properly by connecting it to a power source. Replacement of the filter involves unscrewing the large handle that will release the main filter and then it can be replaced with a new one. The furnace operation is unclear at this time. The flow meter is relatively simple to use. Our team used a DC power supply that provided 24V. This display section is connected to the actual flow meter with the use of a special cord. This cord has multiple wires inside it and has to be connected to the actual meter and the display component in order to function properly. The connections for the wired in each part of the flow meter is very simple, just match the wire colors to the colors on each part. Finally, in order to operate the flow meter correctly and get accurate readings it is necessary to go through the setup menu and select the options for measuring air with a scale of standard liters per minute (STLM).

The 3-way valve is located to one side of the furnace and it controls what side will be tested for composition with the FTIR. If the 3-way valve points towards the inlet junction then the FTIR system will be able to sample the gas before it enters the furnace. Similarly, if the valve is pointed towards the outlet of the system then the FTIR can sample gas after it has traveled through the furnace. If the valve is placed at a middle position (pointing vertically up) then both sides are closed and the FTIR system would not be able to sample anything. One of the proportional valves in our system is used to control the flow towards the flow meter while the other is used to control the flow through the bypass line. Using these two valves in conjunction allows for a wide range of flows to be achieved even when the pump is operating at a constant rate. The top valve controls the main flow through the furnace while the vertical valve located underneath is the one used to control bypass line flow.

Appendix C: Bill of Materials

Table C1. Description of parts used in the prototype

Components	Manufacturer	Part description	Cost
Heated Diaphragm Pump	KNF Neuberger Inc	This is a type of pump with an elastic diaphragm, fixed on its edge, moves up and down its central point by means of an eccentric. In this way the medium is transferred using automatic valves	$4968.54
Ceramic Particulate Filter	Corning DuraTrap	Used to remove particulate matter such as soot	N/A
Heated tape	SwRI	To contain the temperature of the component from losing its heating thus preventing lowering of different component temperatures required	N/A
Thermocouples (Type K)	SwRI	Used to measure temperature	N/A
Micro-Motion Coriolis Flow sensor	Emerson	It is responsible for an accurate measurement of the sample gas emission to meet the specified flow rate requirement of 50 L/min	$4423.50
Micro-Motion Coriolis Flow transmitter	Emerson	Digitally display flow rate with 4 decimal precision	$2267.00
Thermofisher Furnace	SwRI	High temperature heating	N/A

Cart	SwRI	To house all components for ease of transportation from one to place to another	N/A
Converters	SwageLock		N/A
Wooden plate	HomeDepot	This wooden plate was used to make the housing/ countertop for the cart were components were placed	N/A
Probe	SwRI		N/A
Heated Sample line	SwRI	Used to transport the gases pulled from the exhaust passing through different components before the FTIR	N/A
⅜ in. stainless steel tubing (20 ft)	-	Used to transport the gases pulled from the exhaust passing through different components before the FTIR	N/A
2 Proportional Valves	SwageLock		N/A
1 3-way valve	SwageLock		N/A
Two way valves	SwageLock		N/A

Appendix D: Test results

Table E1. Flow test for 30 L/min and 40 L/min

Flow rate set point [L/min]	Valve (control)	Valve (bypass)	Measured flow rate [L/min]
30	open	closed	29.5
	open	0.25	30
	open	0.5	23
	open	0.75	14
	open	open	9.3
	closed	open	0
	0.25	open	0
	0.5	open	3
	0.75	open	8
	open	open	9
40	open	closed	40.8
	open	0.25	41.3
	open	0.5	30.5
	open	0.75	19.7
	open	open	13.3
	closed	open	0
	0.25	open	0
	0.5	open	6.1
	0.75	open	11.1
	open	open	13.2

Table E2. Flow test for 50 L/min and 60 L/min

Flow rate set point [L/min]	Valve (control)	Valve (bypass)	Measured flow rate [L/min]
50	open	closed	50.5
	open	0.25	50.5
	open	0.5	41.4
	open	0.75	27.3
	open	open	16.6
	closed	open	0
	0.25	open	0
	0.5	open	4.1
	0.75	open	13.3
	open	open	16.7
60	open	closed	60.5
	open	0.25	60.5
	open	0.5	48.2
	open	0.75	27.4
	open	open	21.3
	closed	open	0
	0.25	open	0
	0.5	open	8.3
	0.75	open	19.1
	open	open	21.4

Table E3. Flow test for the pump

Flow rate set point [L/min]	Valve (control)	Valve (bypass)	Measured flow rate [L/min]
Pump	open	closed	42.2
	open	0.25	41.9
	open	0.5	32.3
	open	0.75	16.1
	open	open	8.7
	closed	open	0
	0.25	open	0
	0.5	open	3.8
	0.75	open	5.6
	open	open	8.5

Table E2. Pulsations Testing

Time [s]	Flow rate [L/min]
0	42.79
1	42.81
2	42.56
3	42.51
4	41.98
5	42.4
6	42.07
7	42.46
8	43.35
9	42.38
10	42.71
11	42.98
12	43.24
13	43.08
14	42.97
15	42.75
16	42.77
17	42.68
18	42.38
19	42.41
20	42.71
Average and Standard Deviation	**42.67 ± 0.35**

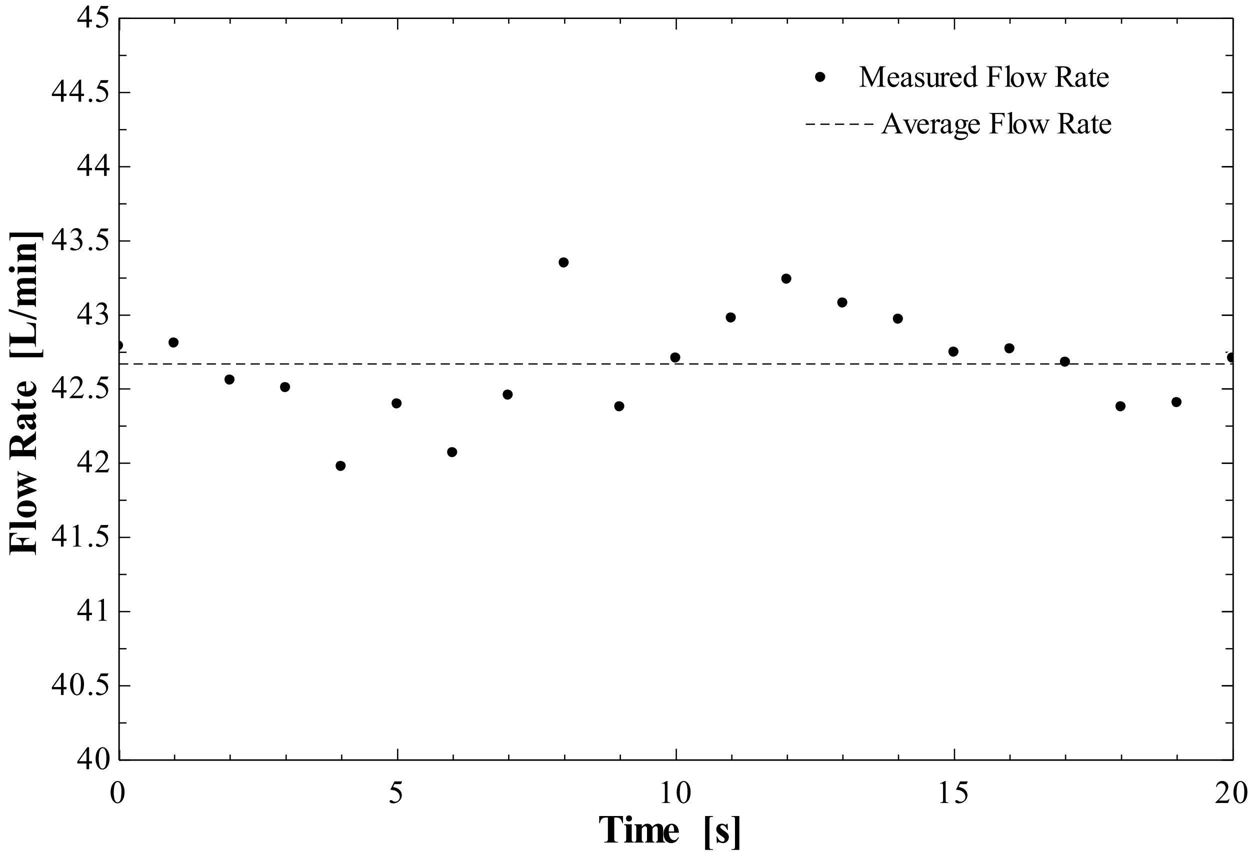


Figure E1. Fluctuation of flow rate for pulsations test