Small Satellite Constellation Electric Propulsion Fluidics System

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Small, less than 100 kg satellites are quickly becoming popular outside university projects. These types of small satellites are also being used as part of constellations. However, to be a part of these constellations they need orbital maneuvering and maintenance capability, and for this the currently available electric propulsion systems are overscaled and expensive.
With sufficient simplification of the operative and propulsive requirements of the constellation satellites, such as performing only orbit parameter changes and drag force maintenance, the complexity of the needed propulsion system and particularly its fluidics system can be greatly reduced. Developing and testing such a fluidics system can then be performed much faster, with reductions in mass, volume and price for the whole system, without sacrificing reliability. By storing propellant in high pressure and using one instead of two mechanical regulators to lower pressure levels to that tolerable by COTS solenoid valves, an effective on/off bang - bang controller - based fluidics system can be built, which supplies a constant gas propellant flow rate and pressures for electric thrusters, that can then create the propulsion forces needed by a small satellite to maneuver and stay an effective part of a constellation. In this paper, a cheap and much smaller version of the fluidics system in an electric propulsion system using argon is introduced and its first test results are shown.

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I. Introduction

The popularity of small satellites less than 100 kg is rapidly growing, with one of their main applications forming up to be constellations. These constellations in turn aim for two applications in specific, remote sensing and communication [6]. Propulsion is essential in creating a microsatellite constellation. As microsatellite missions most likely are not the primary payloads in a launcher, they often end up in a non - optimal constellation geometry, and the satellites in the constellation will have differing orbit parameters [9]. If suitable launches are selected for the creation of the target constellation geometry, such as for example a classical Walker constellation of SSO - orbits, the satellites still most likely have to maneuver to correct final orbits by themselves and maintain them against the environmental forces they encounter during their mission. To be able to achieve this, a propulsion system that can be restarted and is efficient enough to fit into such a satellite scale is needed. A natural propulsion choice for this is then an electric propulsion (EP) system, which has a high efficiency, can be used throughout even a long space mission.
A model satellite of the scale in this work will be a 60 kg LEO microsatellite with a relatively high ballistic coefficient, which needs propulsion for changing its orbital parameters as well as maintaining that orbit against air drag for its mission lifetime. When designing for a worst - case environmental situation, such as a solar maximum, the required ΔV can be as high as 1.2 km / s per satellite [4].
The concept of a constellation however brings benefits to the design of the propulsion system - if a small satellite constellation has redundancy on the level of the constellation itself, for example in the form of spare satellites, the individual systems in its satellites can be simplified and their redundancy limited without compromising the overall mission goals of the constellation, as well as offering a wider selection of different system layouts to choose from. Used as a benchmark in this work, NASA NEXT - propellant management system evaluation [5] for fluidics systems excluded the approach taken in this work, but was aimed for a single, high - cost and yield satellite. In this work the critical assumption thus is, that with proper mission design the requirements on the propulsion system and so fluidics can be significantly lessened, enabling the creation of a propulsion system that can realize such a constellation in the first place, and so solves the redundancy - based choices arrived to by the NEXT - program.
In this paper we'll show performance results of a fluidics system made out of relatively cheap COTS components, which can be used efficiently in a microsatellite to achieve the required pressures and mass flows needed by the EP system's thruster. The propellant in this EP - system is stored in high pressures - in this work up to 150 bars, and can go to over 200 bars. This fluidics system is aimed to be part of an EP - system for a microsatellite constellation, and is designed with the principle of redundancy on the level of the constellation, rather than on the EP - system itself. As a consequence the price and development effort can been dropped considerably, without losing reliability for the overall constellation.
The fluidics system itself consists of one mechanical regulator, one solenoid valve and a custom flow restrictor, produced with additive manufacturing, and the test performed in this work was done using argon. The control happens through a bang - bang controller, where the solenoid valve is opened based on the pressure downstream from it.

II. Designed System Layout

The choice of relying on a redundancy based on the whole microsatellite constellation simplified the layout of the EP - system considerably, as can be seen in Figure 1. This layout is based on NASA's NEXT documentation [5], Yagnanarayana's design for an ion thruster [8] and Smart-1 [2]. The design principle is straightforward - no redundancy is applied, with a drain valve to fill the tank, and downstream of it one isolation valve ensuring no catastrophic failure occurs from failing to hold the high pressures in the tank; a mechanical regulator that handles a wide range of high pressure input, and releases a linear flow up to output pressures of 0.7 bars. The isolation valve is the only component designed specifically for space - use, as it is in a critical role - as such, it is still COTS, but is particularly designed for small satellites. The isolation valve is capable of withstanding up to 500 bars, and has a filter integrated into it.
The mechanical regulator is a commercial - off - the - shelf (COTS) two - way manual regulator, and was tested for a week in + 50 to -5 thermal cycling, as well as for withstanding launch vibrations according to NASA qualification levels [1], and survived successfully both.
After the mechanical regulator drops the pressure to low enough levels, a solenoid valve then drops the propellant pressure even further and controls the desired flow supplied to the thruster by using a bang -

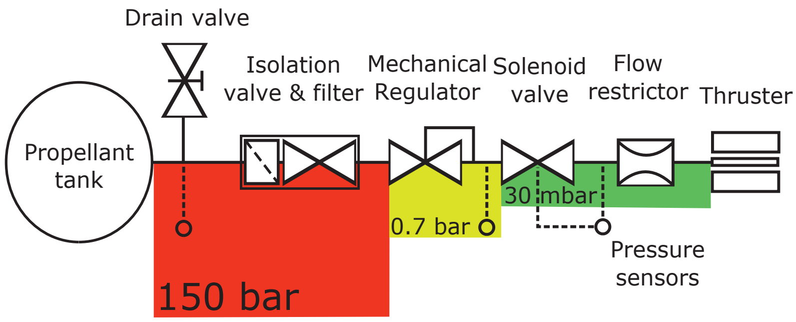

Figure 1. System diagram of the designed fluidics system

bang controller. The controller tries to always keep a given setpoint pressure by opening the solenoid valve once the pressure sensed by the pressure sensor after the solenoid valve has gone below the setpoint pressure. The solenoid valve is also COTS, and is in regular use in high - pressure, high temperature applications requiring a long - term reliability, with up to 500 Hz operation speed possible.

In order to stabilize the flow, a passive flow restrictor was used to smooth instabilities in the flow coming out of the bang - bang controller. The restrictor was custom built using additive manufacturing, and so a fairly complex internal structure as well as mass, volume and power savings were achieved. As a result the volume taken by the fluidics system is estimated to be 100 x 100 x 50 mm in the flight model.

When evaluating and trading off these components of the fluidics system, mass and volume were ranked high, as the system needs to fit into a normally fairly compact microsatellite. As this is a new technological approach flight heritage was not evaluated as an important criteria [7]. Other main drivers for selection were the suitability into this kind of simplified EP system for a microsatellite constellation ; price and lead time were also evaluated to be important parameters for establishing fast and reliable manufacturing chain and reduce time from order to launch schedule, which tends to be tight in the case of getting a synchronized constellation into orbit.

A. Constellation effect on reliability and redundancy

The constellation is the key design factor for the EP and the fluidics system within it discussed in this paper. As a constellation by default contains a coordinated group of satellites, making the satellite identical and adding more of them as redundancy offers an alternative to redundancy on the satellite subsystem level, keeping up the overall reliability of the system as a whole, while making it feasible to build an EP for a microsatellite in that constellation. This type of "safety in numbers" - approach was described (amongst others) in [3] for satellite swarms.

During its mission, the constellation satellite has to perform altitude, inclination changes and air drag maintenance. The EP - system can be used for attitude correction, but is not considered for such a task in this work, and should provide a fixed thrust (again as a result of simplification).

B. Thruster and Tank

As in this work only the fluidics is considered, the tank and thruster have been selected from existing COTS options, so as to be able to have a practically viable design as well as a benchmark to aim for when designing the fluidics system.

As an input from the fluidics, the thruster should have a xenon mass flow of around 1.25 mg/s for the cathode and 0.5 mg/s for the anode (4.26 mg/s and 1.71 mg/s, respectively, for argon - the gas used in testing the fluidics developed here), and the pressure at the inlet should be around 30 mbar. The power processing unit needed by the thruster is taken to be a part of the thruster in this work, is it doesn't affect the fluidics directly.

C. Test setup

The tests in this work were performed in a $1e^{-5}$ mbar vacuum chamber. The pressure sensors used in the test were calibrated using the vacuum chamber pressure sensor as a reference (calibrated until $1e^{-9}$ mbar), and for simplifying the test setup plastic 1.5 mm diameter tubes were used between the solenoid valve and the mechanical regulator, and for flow sensors 3 mm diameter tubes.
A simple arduino was used as a bang - bang controller, with TI's rad - hard TMS570 "Hercules" also designed for the use of the fluidics system, keeping in mind the flight model of the system. The pressure sensors used have a FS accuracy of 0.25 % for 0 - 1 bar range, while the volumetric flow sensor have a 1% FS accuracy for a 0 - 0.1 Nl/min range, and so are well above the accuracy ranges needed for the task. For the tests, roughly 35 (the lab ambient temperature) argon gas was used instead of xenon as the price and availability of xenon is difficult. A diagram of the test setup is show in Figure 2.

We performed 15 minutes testing with different inlet pressures and a series short, 50 seconds setpoint pressures tests, where a selection of triggering pressures controlling the opening of the solenoid valve (also with different inlet pressures to see how this system perform) were applied, and the results are shown in the next chapter. These tests follow roughly the test idea used in Smart - 1 [2].
In addition, long - term testing was performed for several weeks, where the whole fluidics system was stress tested while testing various settings of the mechanical regulator and the solenoid valve, and generally trying out the setup.
The results in turn were recorded using a basic Arduino - RS232 logger measurement setup according to the test setup layout seen in Figure 2.

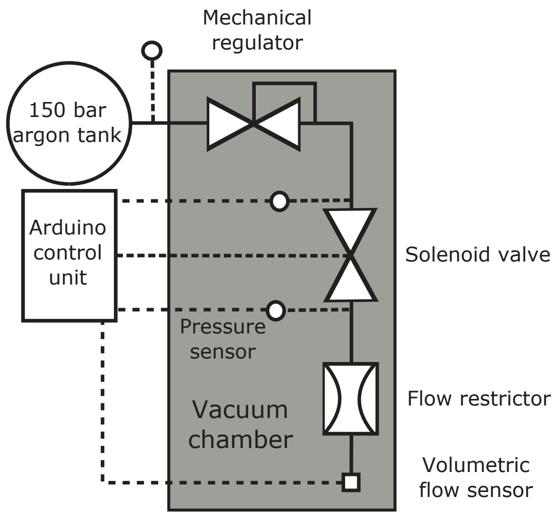

Figure 2. A diagram of the test setup for the measurements presented in this work.

III. Results

In this chapter we show how the fluidics system developed in this work behaves in different inlet pressures for the mechanical regulator and setpoint pressures that control the operation of the solenoid valve.

Performance evaluation of the fluidics system was performed by measuring the time between bang-bang cycles, and were carried out for different inlet pressures going into the regulator, as well as setpoint pressures controlling triggering of the solenoid valve. As shown below, the test setup was controllable and delivers a constant flow both for different setpoint pressures and in different inlet pressures. Flow sensors were calibrated by measuring the zero flow before each measurement run, as well as with an analog flow sensor. The inlet pressures coming into the regulator were also checked with an analog pressure sensor.

Figure 3 shows the recorded flow out of the fluidics, and into the thruster, for four different setpoint pressures - the different plateaus are equally long and a clear difference between each can be seen. From this Figure, looking at the elapsed time between opening the solenoid valve (plot b), one can say that the system is stable and measured flows and pressures do not depend on the inlet pressures. Also the system works in a large range of input pressures, from 50 to 150 bars without any measurable effect.
From Figure 3 b) the elapsed time can be seen - it shows pressure and flow with a step - wise constant value between solenoid valve openings of 500 ms in 40 mbar setpoint pressure, 800 ms in 30 mbar, 2000 ms in 20 mbar and 3000 ms in a 15 mbar. The flow in turn varies between 0.04 - 0.036 Nl/min with 40 mbar setpoint pressure, 0.032 - 0.03 with 30 mbar, and 0.03 - 0.026 with both 20 mbar and 15 mbar. Concluding from Figure 3, one can say that 20 mbar is the lowest pressure where this system goes to and is still controllable. With lower than 20 mbar pressure system becomes unstable. Moreover, for this particular fluidics system and flow restrictor, 30 mbar seems to produce the most stable flow.

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For understanding the system's stability, longer period time series were measured for inlet pressure of 50, 100 and 150 bars, results of which are shown in Figure 4. This figure shows measurements (pressure after the solenoid valve, elapsed time and volumetric flow) for a 30 mbar setpoint pressure (chosen based on Figure 3 results), during a 15 min time period. The pressure signal in Figure 4 is a cyclical, rapid rise and more gradual fall - signal, which when 30 mbar is encountered, triggers the solenoid valve to open up and rises rapidly again - thus the sharp cut - off seen in the snapshot of the measurement, Figure 5.
Based on these measurements, the measured minimum and maximum values for flow, and the elapsed time for the system are 0.25 - 0.003 Nl/min and 113 - 1500 seconds, respectively. These values are consistent with results from Figure 3. Furthermore, from figure 4 we can say that there is no drifting in the elapsed time. In order to be able to determine longer - term behaviour, we also averaged the whole dataset for different inlet pressures to see if there was any drifting, result were that system does not drift in time. Standard deviation of the flow measurements were 0.002 Nl/min for all measured inlet pressures, translating into around $\pm$ 10 % variation in the flow.

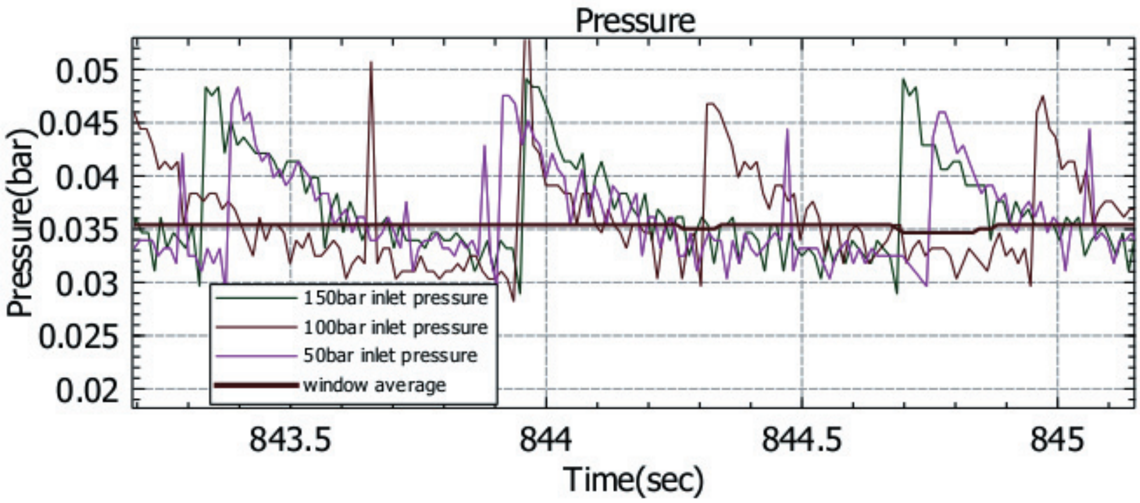

Figure 5. Snapshot of pressure variation after solenoid valve for constant setpoint pressure of 30 mbar

IV. Conclusion and future work

In this paper is is shown that using a novel design approach based on the concept of constellation microsatellites cheap COTS components, and additive manufactured parts it is possible to design and validate a critical part of an EP system, the fluidics.
Results here indicate that the proof - of -concept system shown in this work produces a steady flow with a small enough variation, and can already now fit into several COTS - available thruster systems.

As future work, the thruster part can most likely also be simplified with the same principle simplification thanks to the overall reliability offered by a microsatellite constellation.
Also a more detailed study of the very promising additive manufacturing technique used in designing and developing the flow restrictor in this work should be performed - this technique might enable faster, more complex and cheaper development of a larger portion of the fluidics system, such as the support structure, or even the rest of the EP - system.

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Acknowledgments

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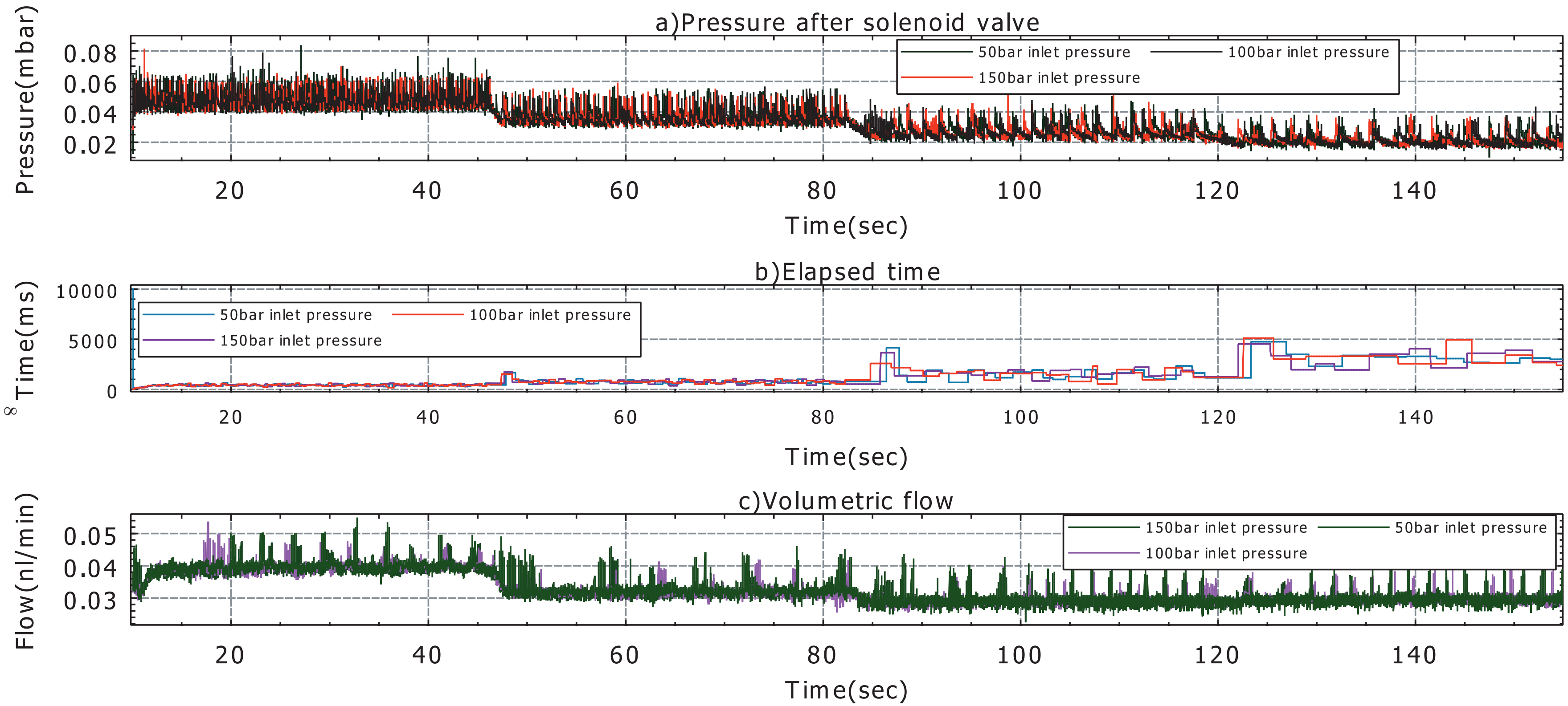

Figure 3. a) shows the measured pressure after the solenoid valve, which is used as a triggering pressure for the valve. In all of these three plots, four different setpoint pressures were used, and so have formed four clear plateaus in the plots. b) shows time between the control signals for the bang - bang controller that open the solenoid valve, and c) shows measured flow after flow restrictor, at end of the fluidics system going into the inlet of the thruster.

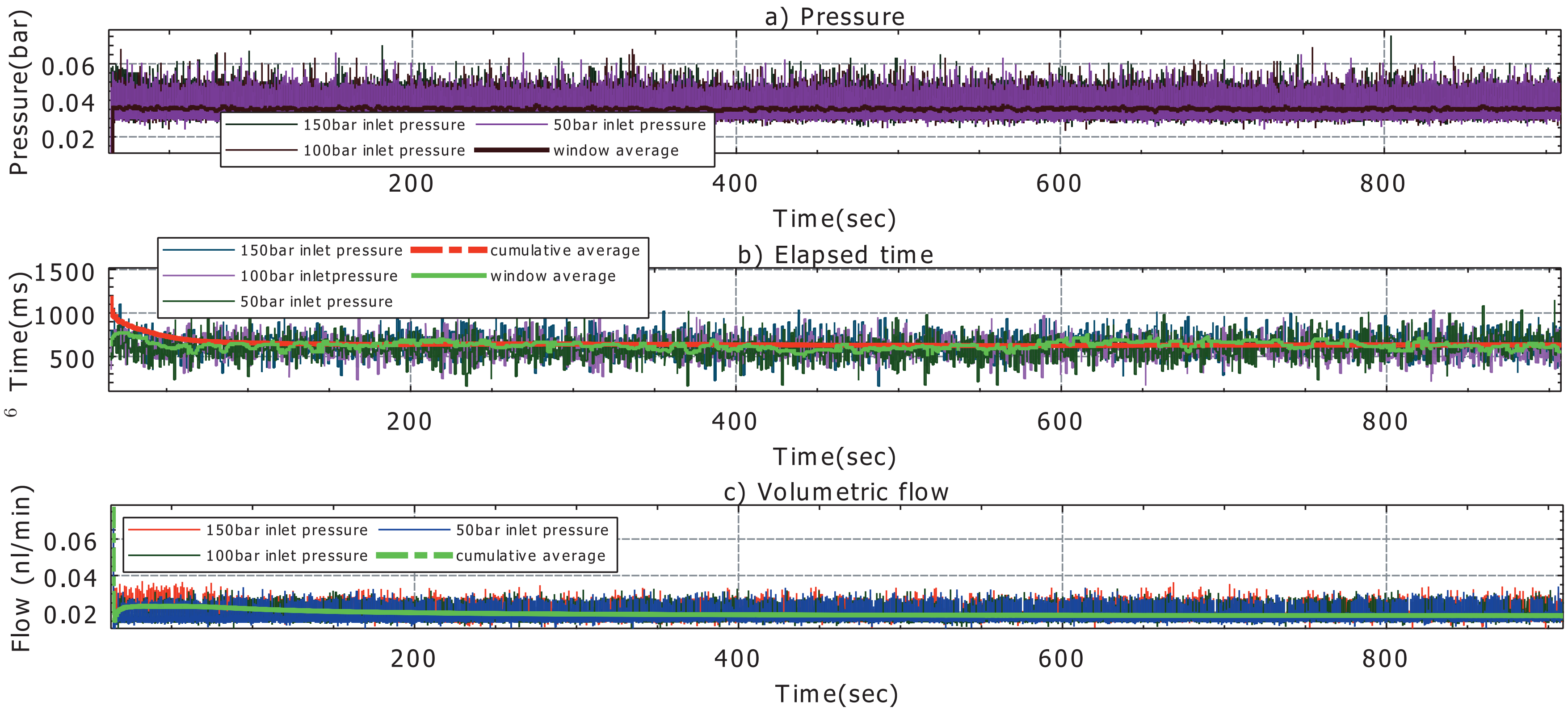

Figure 4. a) Elapsed timed for the bang-bang controller control signal when opening the solenoid valve - here cumulative average represents the mean value and the windows average represents small variations in the data. b) Volumetric flow for different inlet pressures shows constant values for measurment period and cumulative average shows that there is no drifting, and 0.002 Nl/min standard deviation. The large values at the beginning of the flow measurements are due to a calibration error. c) The control pressure for solenoid valve was chosen to be 30 mbar, and stays stable throughout the whole measurement period.