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CONCEPTUAL DESIGN OF A CLEAN AIR ENCLOSURE TEST BENCH FOR MICRODEVICES

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Abstract. *An environment to handle microdevices is a challenge because the natural dusts have a size which is relatively big when compared to the microdevices. The dusts might cause irreparable damage to microdevices such as short circuit in electronic systems, clogging in microfluidic systems, and even corrosion in the materials. The dust is a real challenge when facing the micro and nano world whether during fabrication, integration, testing and / or in actual use. In order to overcome this challenge, the CEFET/RJ research group of Thermal Science in Micro and Macro Scale designed a conceptual clean air enclosure to be used for manufacturing, assembling and testing of microdevices. The air clean enclosure system is designed to have a full control of the cleanliness, pressure, temperature and humidity. Additionally, it is used to perform different kind of experiments using different atmosphere conditions.*

Keywords: *Clean air enclosure, Microdevices, Cleanliness, Workplace*

1. INTRODUCTION

The microdevices, or microelectromechanical systems (MEMS), are getting even more popular with application in areas such as medicine, aerospace, oil and gas, communication, photonic, among others. The possibility to have a high integrated systems as sensors and actuators, or as micromachines, can be seen as a technologic revolution in our society. It is clear the challenge to miniaturize the conventional systems into a small chip. The challenge is not only in the device itself, but also in the environments used to handle the microdevices (Maluf and Williams, 2004; el Hak, 2006; Beeby *et al.*, 2004).

The typical particle size can be divided into visible and invisible to our eye. Most of the particles are invisible to our eye such as carbon black, bacteria, virus, oil vapor, pollen, atmospheric dust, etc. The human being is also sources of these particles. They are released into the air through scaling of skin, hair, breath, cosmetics for personal use and linen garments. The dusts cause inappropriate behaviors in microdevices such as short circuit in electronic systems, clogging in microfluidic systems, and even corrosion in the materials. Due to it, the microdevices need to be handled in a controlled atmosphere where cleanliness level is quantified by the number of particles per cubic meter. Usually, it is handled in a cleanroom where the concentration of airborne particles is controlled, and the cleanroom environment is built in order to minimize the introduction, generation, and retention of the particles. Currently, the cleanroom is being used in different industrial applications such as smartphone components, gyroscopes, genetic engineering, heart valves, lenses, computer memories, cardiac by-pass systems, and even brewery production (Maluf and Williams, 2004; Whyte, 2001; ABNT, 2005).

For instance, a class 1 (ISO3) cleanroom permits no particles in the size range bigger than 5 μm, and just 3 particles for each cubic meter of 0.3 μm and smaller (Torreira, 2004; ABNT, 2005). However, to maintain a cleanroom at this level of cleaning is quite expensive, and, sometimes, it does not justify the cost. To overcome this issue, the size of the clean environment can be designed according to the application being versatile and economic.

The cleanliness level is classified according to ISO 14644-1 through the following equation:

$$Cn = 10^N \times \left(\frac{0,1}{D}\right)^{2,08} \quad (1)$$

where Cn is the maximum permitted concentration (in particles/m3 of air) of airborne particles, N is the IS0 classification number which it is from 0,1 to 9, D is the considered particle size in μm, and 0,1 is a constant with a dimension of μm (Whyte, 2001; ABNT, 2005).

The research group called Thermal Science in Micro and Macro Scale from CEFET/RJ Itaguai is developing a clean air enclosure to fulfill the group demand and the cooperation network. The clean air enclosure might be used from the manufacturing of the device to the testing of the final assembled device in a controlled environment. The clean air enclosure might be used from the research to the teaching point of view. It will be an opportunity to introduce the newest technology which is under development the microsystems to undergraduate and graduate students.

The main goal is to design a conceptual clean air enclosure test bench with the feature to have a cleanliness level as class 100 (ISO5). It allows different kind of tests in micro and nano scale such as microfluidics, microelectronics, lab-on-a-chip, photonics, among others. The usage of different atmosphere conditions during the experiment is an important feature. In addition, moving the test bench around the laboratory increases the range of experiment possibilities allowing, for instance, a better positioning close to a heavy equipment (Griffin, 2004; Moore *et al.*, 2009).

2. REQUIREMENTS

The clean chamber shall have a controlled envirenment, by meaning to control the cleanliness level, vibration, pressure, temperature and humidity. The cleanliness level shall be according to class 100 (ISO5). Other important features which the clean chamber shall have are: allow the inside of the chamber to be viewed; to handle the microdevice avoiding opening the chamber; safety valve to avoid abnormal pressures; feedthrough devices to allow the instrumentation inside the chamber; fittings and parts to connect the vacuum pump and the air ventilation to the clean chamber; and to allow assembling a new part in order to increase the chamber size.

The clean air enclosure can be used, in principle, in three different applications:

Device manufacturing - One of the most important parameters during the microdevice manufacturing process is the environment cleanliness quality. A very small particle may damage the final manufacturing result. Other parameters which are also important for certain manufacturing processes are humidity, temperature, pressure, vibration, and the gas type to compose the environment.

Components assembling - The number of particles in the environment is essential packaging or assembling the parts. A dust environment might cause inappropriate behaviors such as short circuit in electronic systems, clogging in microfluidic systems, and even corrosion in the materials. Additionally, the humidity is also a parameter which might damage the system due to the water condensation on its components providing oxidation. Usually during packaging and/or bonding it is required clean envirenments, and sometimes it is required a specific vacuum level in order to have a satisfactory assembly.

Device testing - Cleanliness may be an important parameter for testing, but having a turbulent flow inside the enclosure during the testing greatly affects the results. Thus, considering the microdevices are already properly packaged avoiding the presence of unwanted particles, there is no explicit need to use the parameter cleanliness (save some exceptions). Due to its complexity, the experiments may require different scenarios. The basic conditions or parameters considered in this paper are controlled temperature, pressure, humidity, vibration, and also the use of different gas envirenment (different types of gases).

The desired requirements to design a proper clean air enclosure are presented in Table 1, considering the three possible applications manufacturing, assembling, and testing.

Table 1. The desired requirements used in the conceptual design

Structure	Ergonomic, Strong and Transparent
Interface	Feedthrough systems
Temperature	from 15°C to 50°C
Pressure	from 10 kPa to 150 kPa
Humidity	up to 75%
Gas environment	Ar, CO_2, O_2, N_2

3. TECHNICAL DETAILS

Figure 1 shows the schematic drawing of the clean air enclosure over the workbench. The whole structure is made of stainless steel. The workbench has lockable castors which allow moving around the lab. The structure was designed to have free space under the workbench to place the ventilation, vacuum and air conditioning systems, avoiding direct contact to the main structure. As a consequence, it avoids vibration in the clean air enclosure structure.

The clean air enclosure was designed having a front hinged lid which allows accessing inside the enclosure, see Figure 2. The front hinged lid is divided into two parts, one vertical and another inclined. The vertical part is where the sliding gloves are placed. In case the sliding gloves are not being used, it is advised the glove hatches be closed. The enclosure bottom part is made of stainless steel providing better chemistry and mechanical resistance. The airlock is designed to minimize the effect in the enclosure during operation when it is necessary to add or remove a part.

Inside the enclosure, there are two air distribution tubes connected to the atmosphere conditioning system by a set of hoses and registers. The atmosphere conditioning system can be seen in Figure 3. The air which comes from the enclosure pass through the diffuser, and then it is pre-filtered. There is a turbo axial fan between the pre-filter and the HEPA filter.

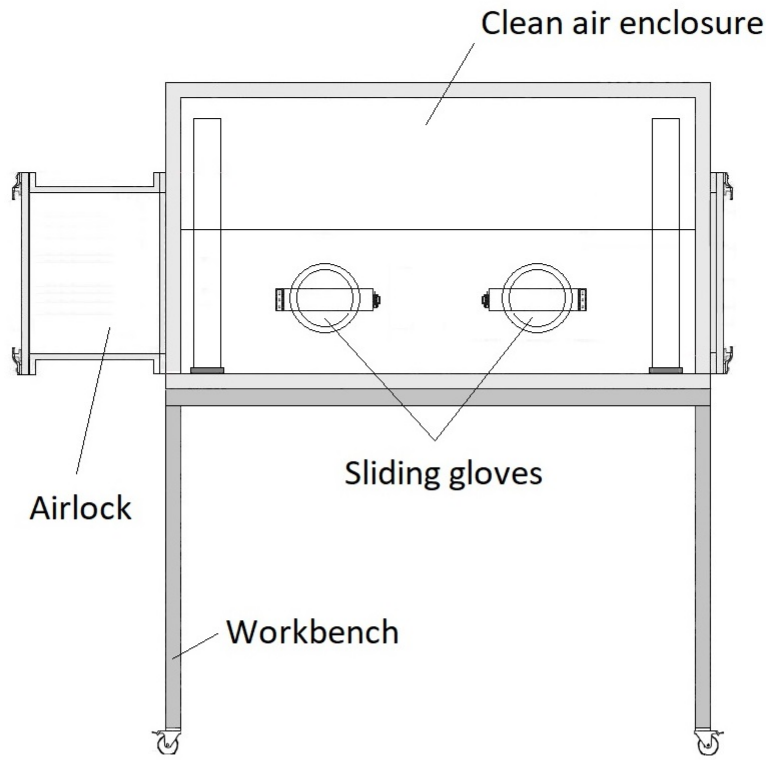

Figure 1. Sketch of the clean air enclosure over the workbench.

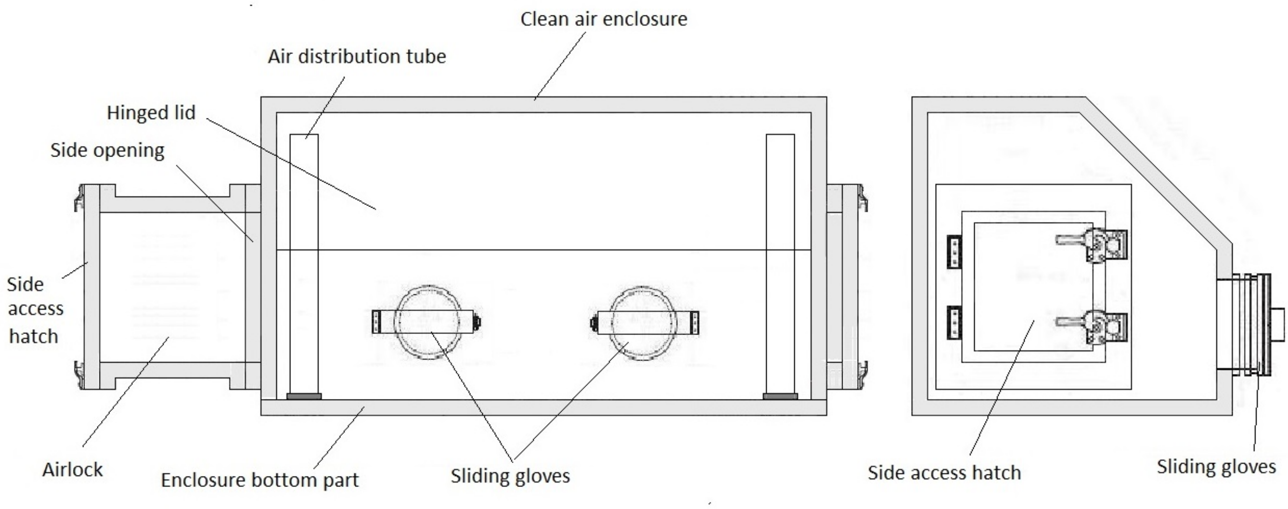

Figure 2. Sketch of the clean air enclosure showing the details.

The turbo axial fan, which is controlled by electrical frequency, has the function to suck air through the pre-filter. Turbo axial fan is driven by a brushless motor so that there is no carbon particle production. The HEPA filter is responsible for the main cleanliness, retaining the smallest particles. The pre-filter and the HEPA filter systems have a mechanism that allows changing the filter element without stopping the process. Even though many filter element manufacturers report that the average filter element lifetime is about one year, it is essential to have the possibility of replacement if needed.

Just after the HEPA filter system has an axial fan used to impulse the filtered air to the finned heat exchanger, improving the heat transfer coefficient. The axial fan is also driven by a brushless motor avoiding the carbon particle production. The finned air-water type heat exchanger is intended to control the temperature of the circulating air through the exchange of heat from a working fluid supplied by an autonomous refrigeration unit, see Figure 4. Then, the filtered air passes into a humidity system where the air humidity and temperature will be controlled. The humidity system contains a set of micro sprinkler nozzles that spray water in a controlled manner and a set of electrical resistance allowing an adjustment of the air humidity and temperature. After all, the filtered and humidified air is sent back to the clean air enclosure through the set of hoses and registers.

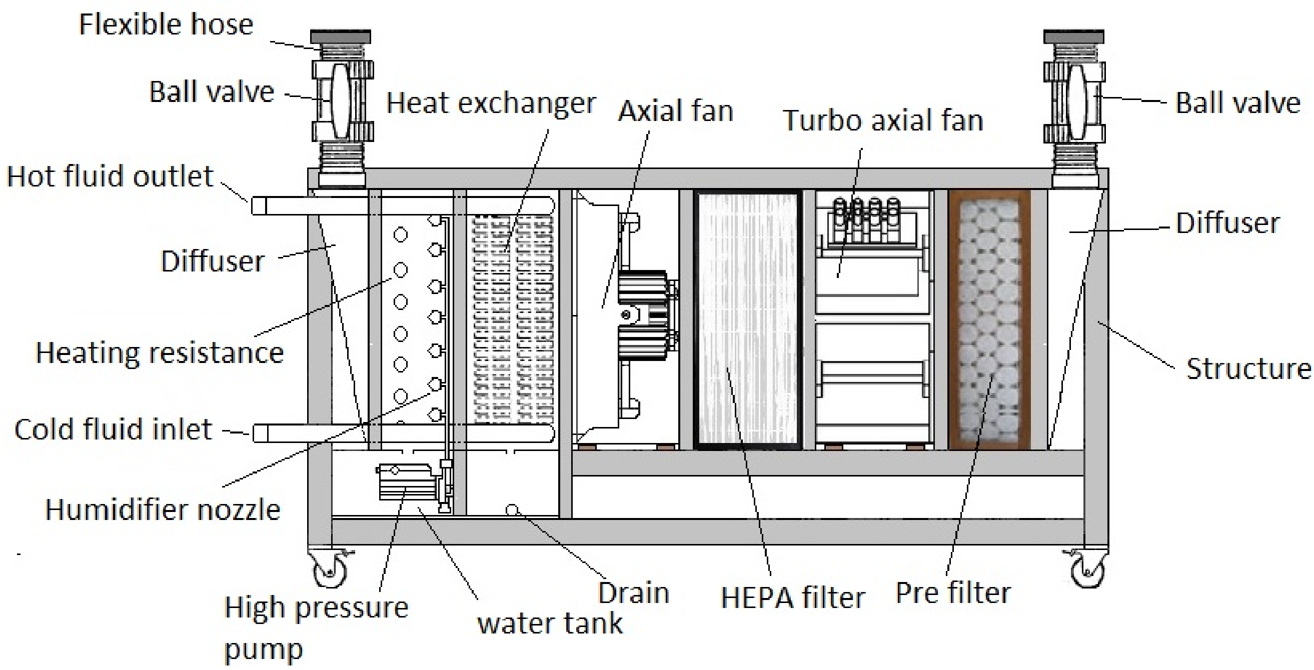

Figure 3. Internal cut sketch of the atmosphere conditioning system.

The atmosphere conditioning system regulates the temperature and relative humidity to the desired values. The air might be cooled or heated to a selected temperature within the range of $+15°$C to $+50°$C with an accuracy of $\pm1°$C. The relative humidity might be controlled to a selected value between 15% and 90% relative humidity with an accuracy of $\pm3\%$ relative humidity.

Figure 4 shows the sketch of the autonomous refrigeration unit. The working fluid is used to cool down the filtered air in the heat exchanger of the atmosphere conditioning system. The heated working fluid goes through the inlet tube of the autonomous refrigeration unit to the shell and coil heat exchanger. In the shell and coil heat exchanger, the working fluid is cooled down and then stored in the stabilization tank.The temperature is kept constant in the stabilization tank because of a storage system where the phase change of a thermal fluid occurs. A pump with flow control pumps the working fluid through the outlet tube to the heat exchanger of the atmosphere conditioning system.

A conventional air conditioning system is applied in order to cool down the working fluid in the shell and coil heat exchanger. The shell and coil heat exchanger is the evaporator. The refrigerant is evaporated in the evaporator and pumped by a compressor to the condenser where the gas is compressed losing heat and condensing. The refrigerant flow is controlled by the expansion valve, which drops the pressure at the evaporator, allowing the exchange of heat through the refrigerant evaporation.

The atmosphere conditioning system can be replaced by vacuum system and alternative atmospheric system, see Figure 5. The vacuum system is equipped with a set of two vacuum pumps from BOC Edwards and their control systems, allowing to adjust the desired vacuum level (up to 10 kPa). This system is connected to the enclosure by a specific connector which does not transmit vibrations. The alternative atmospheric system is assembled on a chassis with the capacity to hold up to six 1.5 m^3 cylinders. Specific valves are used depending on the gas type allowing to pressurize the enclosure with the desired gas. The gas pressure at the enclosure is controlled by pressure regulators and valves.

The alternative atmospheric system is associated with the vacuum system. In order to have a specific gas atmosphere at the enclosure, it is needed first to vacuum the enclosure and, then, to fill with the desired gas.

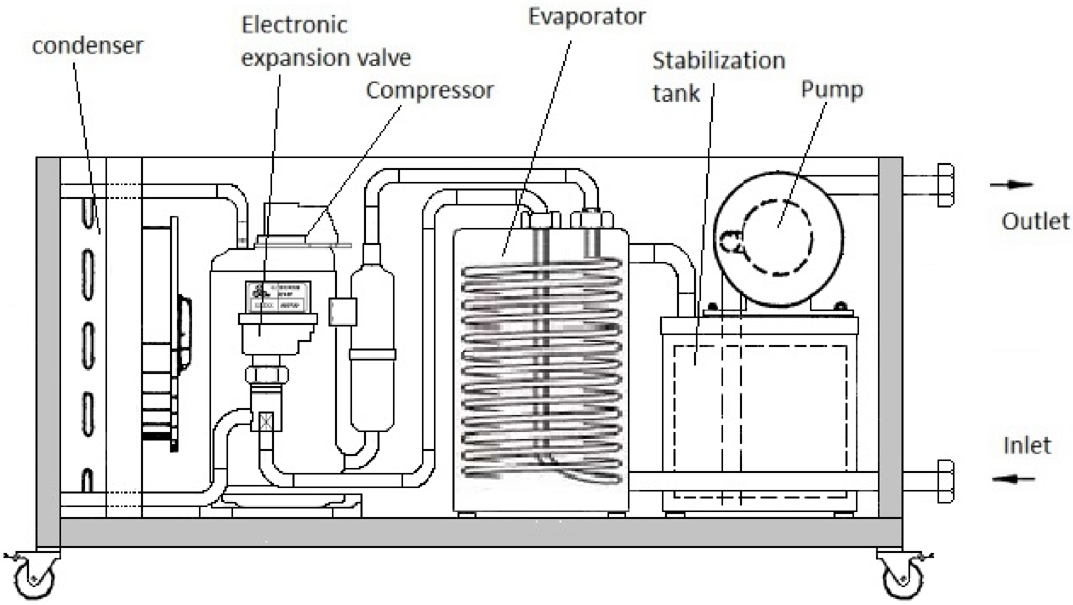

Figure 4. Sketch of the autonomous refrigeration unit.

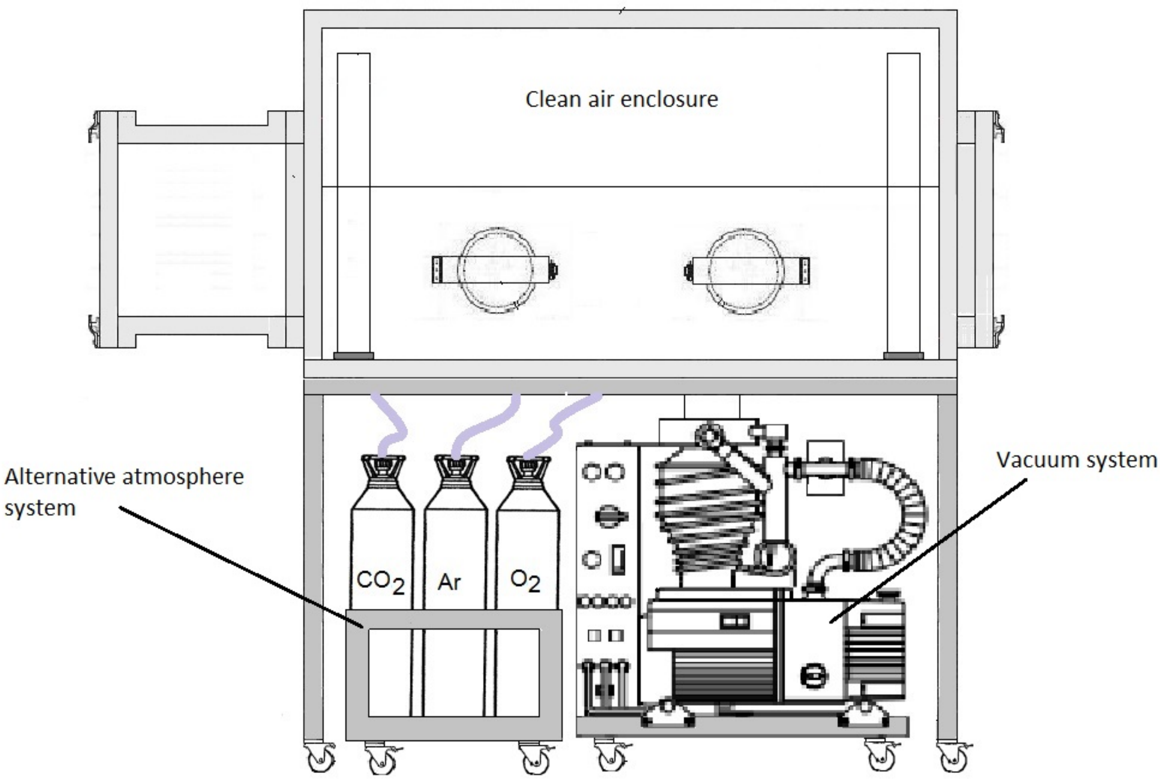

Figure 5. Sketch of the vacuum system and alternative atmospheric system.

Figure 6 shows the schematic drawing of the complete configuration of the clean air enclosure with a controlled atmosphere, where it is possible to have a general idea of each of the components for this configuration. Remembering the autonomous refrigeration unit system and the atmosphere conditioning system might be replaced by the vacuum system and the alternative atmosphere system according to the desired activity.

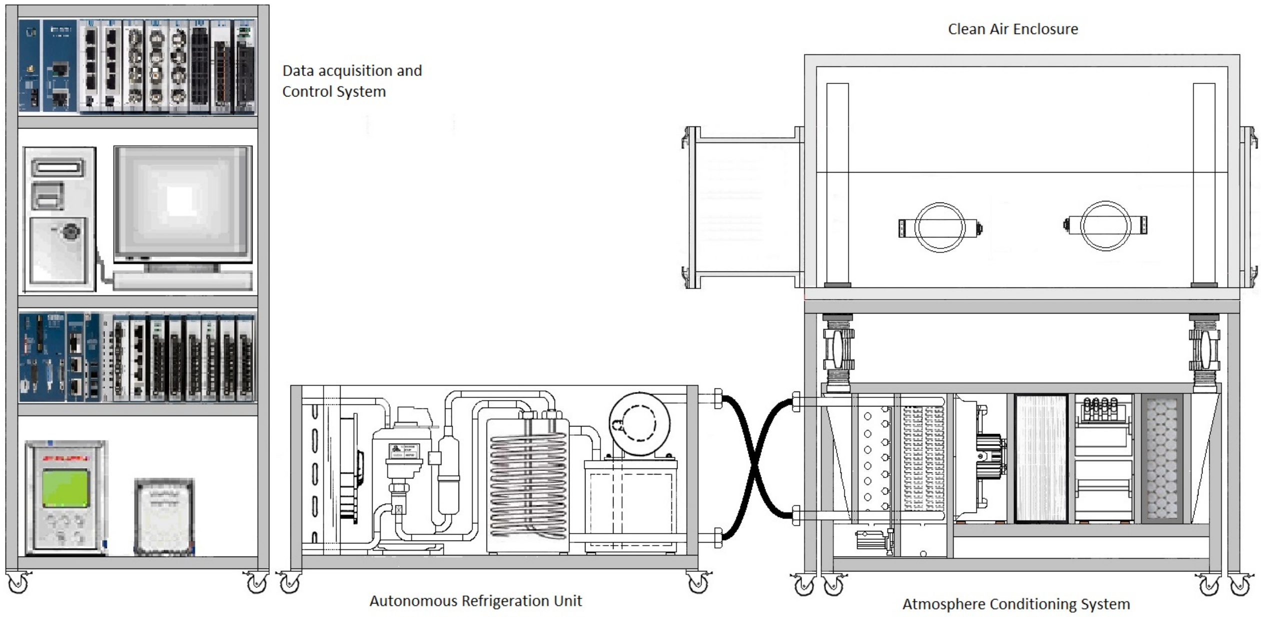

Figure 6. Sketch of the data acquisition and control system.

On side of the workplace there is a cabinet with few shelves where it is placed the data acquisition and control system composed by National Instrument equipaments, computer and power supply, see Figure 6. It is from where the clean air enclosure system will be controlled in a real time through the LabView software, besides to save the data to further analysis. Few sensors are placed at strategic positions in order to read the interested parameters such as temperature, pressure, humidity, voltage and current.

The control system has the function of controlling the operation of each component of the atmosphere conditioning system to operate under the conditions established for the experiment to be performed. In order to control the enclosure atmosphere condition, a series of sensors are installed to measure the needed parameters to control the system. The control system acts simultaneously on the autonomous refrigeration unit. The same happens when using the vacuum system and the alternative atmosphere system.

The clean air enclosure system is also equipped with microscope image system coupled to the data acquisition system. It allows to see the microscope image during and after the experiment. In addition, other equipaments, but equally important, are necessary to perform a proper and safety experiment such as a fire extinguisher CO2 type, an isothermal tank to regulate the fluid temperature during the experiment, syringe pumps and infrared camera.

4. DISCUSSION

4.1 Applications

This clean air enclosure can be used in three different applications device manufacturing, components assembling, and device testing. Different approaches are needed in each one of these applications.

Device manufacturing

To Consider the clean air enclosure system to be used as a device manufacturing application, it is necessary to understand the possibilities. Obviously, few of the conventional manufacturing processes might not be compatible with the cleanliness such as the mechanical cutting processes (milling, turning, grinding, polishing, etc.). Those processes typically produce too many particles which make impracticable to be used. However, there are a few possibilities such as surface coating, etching, polymer deposition, micro-forming (stamping, extrusion, forging, bending, deep drawing, incremental forming, superplastic forming, hydro-forming, etc.), hot embossing; micro/nano-imprinting, resistance soldering, vacuum soldering, bonding, gluing, and others. All those possibilities need to be studied and researched in order to make it compatible with the clean air enclosure. It might or might not change a bit the current design (Razali and Qin, 2013).

Components assembling

One of the main challenges when miniaturizing is the interface between the micro and macro scale. For instance, the business market value of the MEMS packaging is growing faster than the MEMS device market (Jolivet and Mounier, 2017). It is essential to have a way to assemble the components. The clean air enclosure is an interesting way to assemble the components with no risk of short-circuiting and microchannel clogging. All kind of devices might be assembled using the clean air enclosure from a simple integrated circuit, sensors, actuators to a complete nano/picosatellites.

Device testing

From the device testing point of view, there are plenty of possibilities. To test lab-on-a-chip devices for different applications with total control of cleanliness, temperature, pressure, gas atmosphere, and so on. To test all kind of micromechanical systems, sensors and actuators. For instance, micro propulsion systems can be assembled and tested. The micro propulsion systems can be characterized in an oxygen free atmosphere avoiding oxidation and avoiding dust particles which can block the nozzles (Guerrieri *et al.*, 2017; Silva *et al.*, 2017). To test the devices in the clean air enclosure provides better atmosphere condition with very low dust level. It increases the experiment reliability in this scale since the small dust particle can interfere significantly in the results.

4.2 Versatility

This conceptual design of a clean air enclosure test bench is an interesting way to reduce the high cost to maintain a cleanroom. One of the possibilities is to have a few clean air enclosures assembled in series as a production line where the device is manufactured, packed, assembled and tested.

The use of different atmosphere conditions during the experiment is an important feature allowing to increase the system application possibilities. To move the test bench around the laboratory is another important feature allowing a better positioning close to the desired equipment.

Usually, a cleanroom uses two different flow regime to remove the particles, known as turbulently ventilated (nonunidirectional) and unidirectional flow (laminar flow) cleanrooms (Whyte, 2001). The point is that the flow regime depends on the application it is used. A further research have to be done considering the specific activity requirements.

5. CONCLUSION

The air clean enclosure system with the controlled atmosphere in this work provided an overview of the procedures required to obtain environments with the controlled air contamination and all basic parameters needed to construct it. Based on these principles, which almost all are defined by a specific norm, it was possible to address constructive aspects of the air clean enclosure, especially how the air conditioning of such environments should be done.

The clean air enclosure conceptual design showed to be an interesting test bench to handle microdevices. It can be used to manufacture, assemble and test microdevices. The air clean enclosure system was designed to have full control of the cleanliness, pressure, temperature, and humidity.

Considering the clean air enclosure system constructive aspects, it was possible to identify a few key points to have the desired system performance such as: the seal joints between the polycarbonate plates and the stainless steel frame; the feedthrough system seal of the electrical connections for the sensors, the actuators, and the power system; the closing system of side access door doors using a system of airtight doors; the flow regime in the enclosure has to be defined according to the application.

The next steps will be a focus on the optimization of the important parameters to have the final design of the clean air enclosure system according to the specific application. Then, the components (the parts) will be manufactured, the instrumentation will be connected and tested, and the whole system will be characterized. After all, it will be asked the regulatory agencies to certify the test bench and, then, the test bench will be ready to test properly the microdevices.

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