Project of Strategic Interest NEXTDATA

Deliverable D1.1.3
Report on the technology related to the development of portable and autonomous monitoring systems

Resp: Paolo Cristofanelli, CNR-ISAC

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1. INTRODUCTION

Access to quantitative information on remote regions is crucial in order to arrive at a complete picture of the current climatic and environmental situation. Currently, however, information from remote regions is still scarce and often difficult to access. It is therefore of primary importance to increase the number of climate-environmental observation networks. Especially at high altitudes, it is important to obtain information from the greatest possible number of measurement locations, well distributed in space and installed at different heights, due to the extreme orographic and climatic complexity of mountain terrains. Particularly for atmospheric parameters, meteorology and air quality, these observations should be executed in compliance with the guidelines defined within international reference Project and Programmes (e.g. WMO, GAW-WMO, ACTRIS).

Remote areas are difficult to access and characterised by complex and extreme environmental conditions. Thus, to perform continuous monitoring for high-quality data is a challenging task also for the problematic logistic conditions that often prevent the use of complex and advanced scientific instrumentation.

To reduce this gap of in-situ information and to cope with these technical and operative problems, the development of measurement systems characterised by easy transportability and mobility, by a "plug-and-play" concept and by a limited power consumption, able to allow the independence from the presence of a power distribution network, is necessary.

Ideal characteristics of a portable monitoring system to be transported and used in remote locations, should be:

a. Transportability of the components as checked luggage (with gross weight lower than 30 kg);
b. Easy assembly of the components on site;
c. Easy maintenance (use of changeable components);
d. Possibility to be powered by different sources (renewable or not) with a module able to accumulate power to operate the instruments continuously;
e. Possibility of facing different climate conditions, including extreme cold and extreme hot conditions;
f. Possibility of stand-alone functioning, in order to carry out monitoring activities also where the presence of operators is not possible;
g. Possibility of reducing power consumption and managing environmental events (e.g. ice formation, high environmental humidity);
h. Availability of systems for data managing and data backup;
i. Availability of a remote connection to transmit data and control the system.

In this document, we report the results of a study concerning the evaluation of the technology used for a transportable and energetically autonomous measurement system, originally started in the framework of the SHARE project. This system is able to perform continuous measurements of surface ozone, carbon dioxide, aerosol size distribution, aerosol particle number and meteorological parameters.

2. GENERAL DESCRIPTION OF THE SYSTEM

2.1. Synoptic

The system considered for this study is a compact embedded station for climate monitoring. It is conceived with 2 different pieces that are easily assembled. The first piece contains all instrumentation while the second piece is used for the storage of standards, chemicals and batteries. It is a system with 50W consumption and a system weight of 30kg (without utility box). This system will be installed in remote sites connected to renewable energy sources. The box integrates the following parts (figure 1)

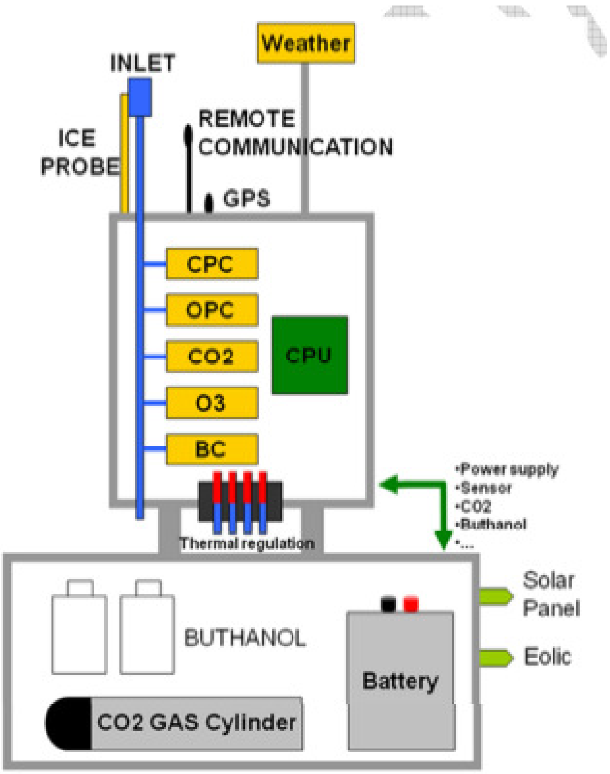

Figure 1 Schematic description of the box with the instrumented components containing instruments for gas and aerosol phases as well as the acquisition and communication systems. The second box contains batteries and standards / chemical for the instrumentation.

Overall, the system can be transported separately:

- n. 1 box for solar panels that can be folded and compacted into 80 x 130 x 20 cm and 10 kg weight;
- n. 1 box for instrumentation (external) in 38 x 50 x 65 cm and 18.5 kg approximately;
- n. 1 box for battery housing and energy production 80 x 60 x 40 cm, and 80 kg.

Figure 2 is showing the entire system assembled for operational use.

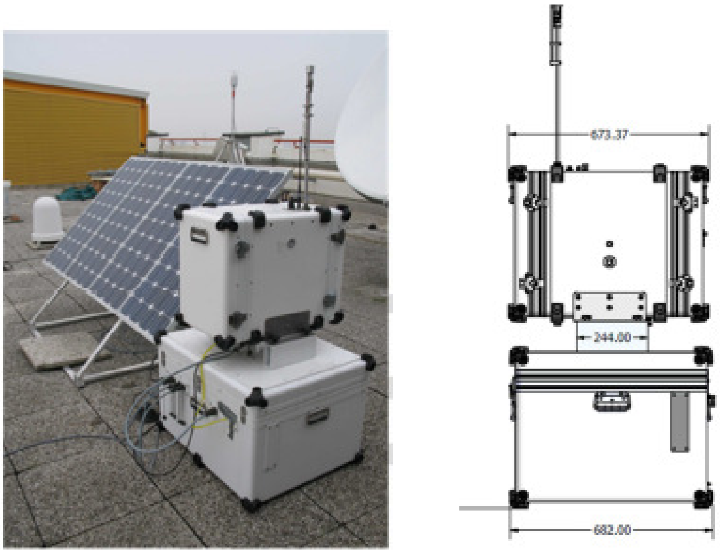

Figure 2 External view of the system (left). Scheme with external dimensions of the system (right)

2.2. Presentation of the entities

To provide a detailed description of the system, it easier to divide it into 5 different entities:

1. **Box mounting structure** which consists of the original boxes used to host instruments and batteries. It is a fundamental piece of the system since it will be protecting the box against both varying temperatures, meteorological condition (snow, wind, precipitation, solar radiation) and at the same time it should be resistant enough for transport and easy enough to handle to field operation.
2. **Energy source:** the energy production unit is composed of the energy production unit (solar panels and aeolian system) and of the energy storage system (batteries). It also includes the energy transmission system.
3. **Sampling system;** the sampling system comprises the inlets suited for the sampling of aerosol and gases. The main characteristics are efficiency and resistance to adverse meteorological conditions, in particular for temperatures below freezing and high humidity (in particular the presence of clouds).
4. **Instrumentation**: the instrumentation is including measurements for the aerosol phase (size, number and mass as well as absorption coefficient –that can be used to derive BC) and for the gas phase (CO_2 and ozone mixing ratios).
5. **System control:** the overall station should be controlled remotely in order to work unattended for many months. The control of the instrumentation should then be reliable and should provide to the user all information related to the station operation.

The 5 different entities elements are presented in Figure 3. In the subsequent part of the report, each of them will be presented and evaluated separately in more details.

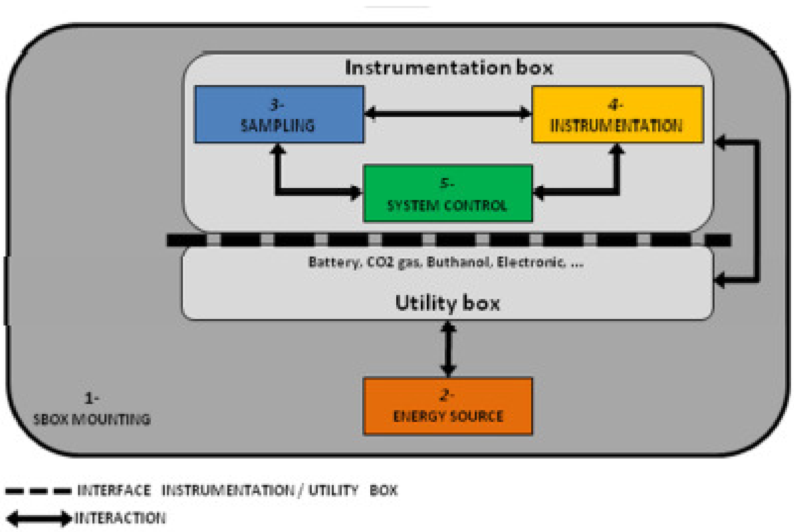

Figure 3 Application diagram.

BOX MOUNTING ENTITY

BOX Mounting Entity (SOME) specifies two boxes: the *instrument box* and the *utility box*. The two Boxes are commercially available from the following manufacturer: BRC77 (Baie Rack Container).

The boxes have the following characteristics:

Composition	Glass fiber and polyester resin
Colour	White for better sunlight reflexion
Protection index	IP 67 and CEM treatment. Shock pads.
Insulating characteristics	Internal temperature range...........................+20...+25 °C External operating temperature.........................-40...+24 °C
Dimension	Module 1 (external)... ....38 x 50 x 65 cm Module 1 (instrument housing)........... ....28 x 41 x 42 cm Module 2 (battery housing)...................... ......80 x 60 x 40 cm
Weight	Module 1 (case)..8.5 kg Module 1 (Instruments and rack) ....10.0 kg Module 2 (battery)...................................... ......80.0 kg

Each box can be easily opened to access the instrumentation. It is equipped with systems that permit strong fixing of the box with cables.

2.3. Instrument box

The instrument box contains the INStrumentation Entity (INSE), the SAMpling Entity (SAME) and the System Control Entity (SYCE). All instruments are mounted in a stainless steel rack that can be easily removed for maintenance operations. Figure 4 shows the front panel of the instrumented box.

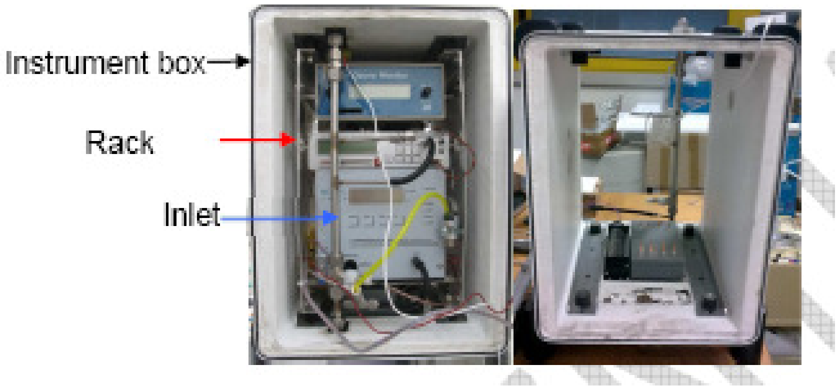

Figure 4 Front panel of Instrumentation Box with and without instrumentation .3 instruments are visible from the top: Ozone analyzer, optical particle counter, condensation particle counter.

Inside the box, the instrumentation is placed respecting the following considerations:

- Display available when opening the front panel
- Space restrictions: 5 instruments and all other devices can be placed
- All instruments are accessible to a single sampling system with limited bends

Figure 5 below shows the choice for placing the instrumentation inside the BOX.

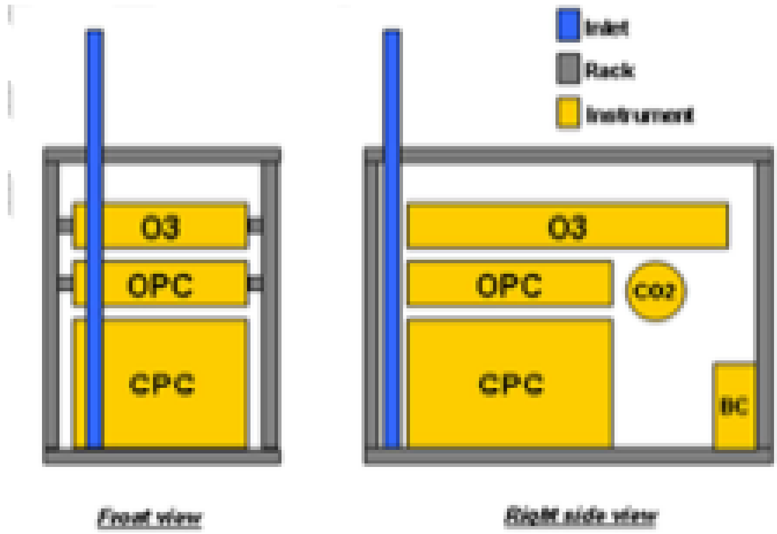

Figure 5 Instruments arrangement in the rack. The CPC (condensation Particle Counter) is the heaviest of all instruments and is placed below also for making the connexion with the butanol reservoir easier. OPC (Optical Particle counter) and Ozone (O3) monitor are placed above the CPC. The instruments for CO2 and BC are smaller in dimension and easier to include in the rack.

2.4. Utility box

The utility box (figure 6) contains the following elements:

- Battery set
- Eolic & Solar charging regulator
- Butanol reservoir & pump connected to the CPC
- CO2 Gas standard cylinder & manometer with solenoid valve connected to the CO2 analyzer
- Electronic sensors monitoring (Temperature, current, voltage, ...)

This utility box cannot be transported with all its features due to its weight (>80 kg) in full operations. However, it is prepared in order to be easily reinstalled once in the field. All connections are simplified to facilitate operations and the space is optimized for easy packaging of the different parts. This box can be opened from different sides if necessary to access all its parts.

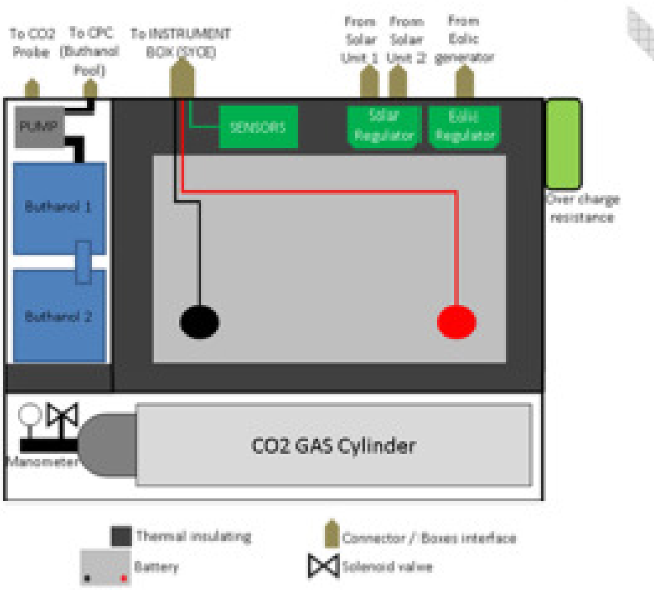

Figure 6 Architecture of the Utility Box. It contains the battery box, insulated with foam, a case for the standardized CO2 gas cylinder and an insulated part for the butanol reservoir.

2.5. Thermal regulation

Thermal regulation of the system is essential for different reasons:

- Avoid overheating of instrumentation in the case of intense solar radiation
- Maintain the instrumentation above freezing temperature even in the case of very low external temperatures
- Maintain the proper conditions for optimal use of the batteries

Heat is mostly produced in the instrument box during normal operation of the instruments. Even if the heat production is limited, the perfect insulation of the box limits exchange with the outside. On the other side, no heat is produced in the utility box but the optimal use of batteries requires functioning temperatures preferably above 10°C. A system based on Heat-Pipe technology transfers heat between the instrumental and the utility boxes. Heat-pipe is a heat transfer device that combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two solid interfaces. A liquid in contact with a thermally conductive solid surface turns into a vapor by absorbing heat from that surface. The vapour condenses back into a liquid at the cold interface, releasing the latent heat. The liquid then returns to the hot interface through either capillary action or gravity action where it evaporates once more and repeats the cycle (Figure 7).

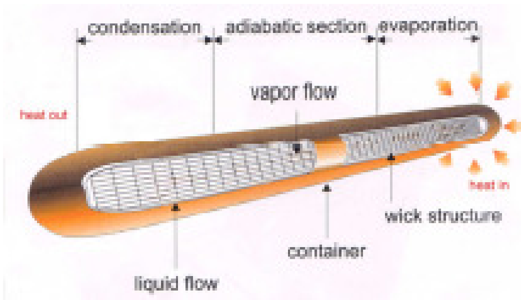

Figure 7 Principle of Heat-Pipe.

The system has eight Heat-Pipes and two fans. One fan is located inside whereas the other one is outside. The fans are enabled or disabled following a temperature threshold defined in the software.

The fluid contained in the heat pipes exchanges between the inside and the outside of the instrument box by changing phase. The process is active as long as there is a temperature gradient. So the action of the fans increases this gradient. The inconvenient of this system is that the process cannot be stopped: the heat pipe must be sized for each specific environment (Figure 8).

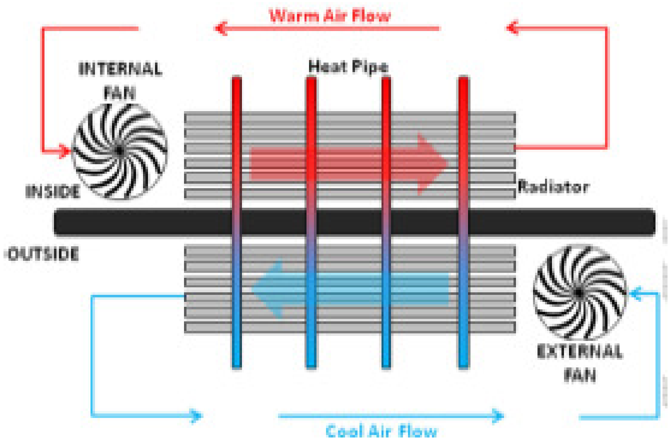

Figure 8 Schematic of the BOX Heat-Pipe system.

To test the efficiency of heat transfer through the heat pipe, we have monitored the temperature variations inside and outside the box for varying atmospheric conditions, during the field campaign carried out in Askole on August-October 2012.

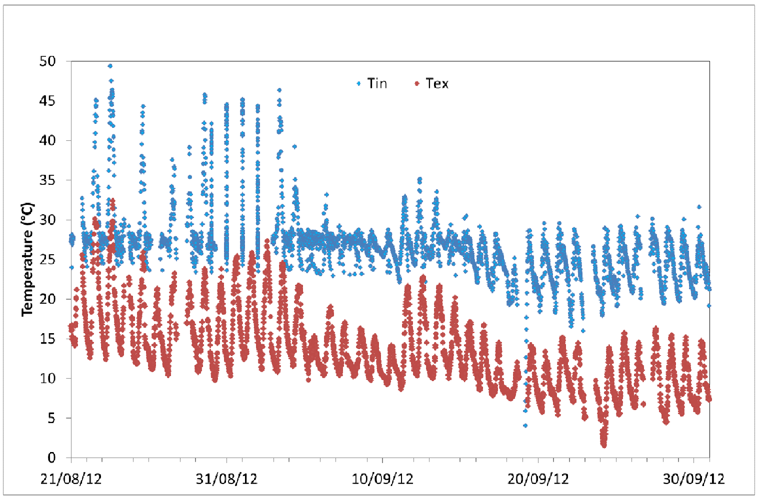

Figure 9: Temperature comparison during test at Askole (Pakistan, 2012)

This chart (Figure 9) represents the evolution of the temperature inside (blue) and outside (red) the instrument box. The external temperature fluctuates from 0°C minimum to a maximum of 32°C whereas internal temperature varies, in the same time, from 20°C minimum to 50°C maximum. For 11% of the time, the system goes outside its proper operation range (typically <5°C and > 30 °C). From these data, we can estimate that the range of outside temperatures for which the box can be used is typically for a maximum of about 15°C.

3. ENERGY SOURCE ENTITY

3.1. Architecture

One of the requirements for this system was the fact that it should be adapted to the high mountain and remote environments and therefore should produce its own energy. The **ENergy Source Entity (ENSE)** allows providing power supply. It consists of solar panels and an eolic generator with associated electronics necessary to charge and protect the battery (Figure 10).

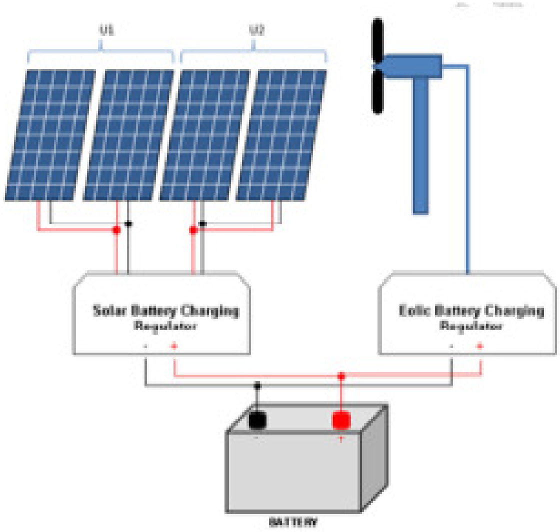

Figure 10 Architecture of the energy entity.

The solar panel provided with the system can provide 80W in standard radiation conditions (1000 W·m^{-2}, 25°C). So by using four solar panels, 320W power is available. In practice, the efficiency of a solar panel is much lower and 4 panels seem a reasonable compromise between cost, weight and energy requirements. For ideal conditions of radiation, the current provided by solar panels reaches about 20A.

Solar energy can only be provided during daytime. In addition, the system should operate under cloudy conditions during which solar energy production is very limited, if not zero.
This is why an additional aeolian generator was added to the system. The aeolian generator can provide a rated power of 350W for a rated speed of 12.5m·s^{-1}. The generator must be modified for adaptation to humid/below freezing conditions with extra-heating system. These are the most complex conditions for which no optimal solution was found. The Aeolian system was acquired from the following manufacturer: Superwind GmBH (Germany). It is a small wind generator suited for under extreme conditions that works autonomously. The electric power generated charges batteries with the efficiency described in Figure 11.

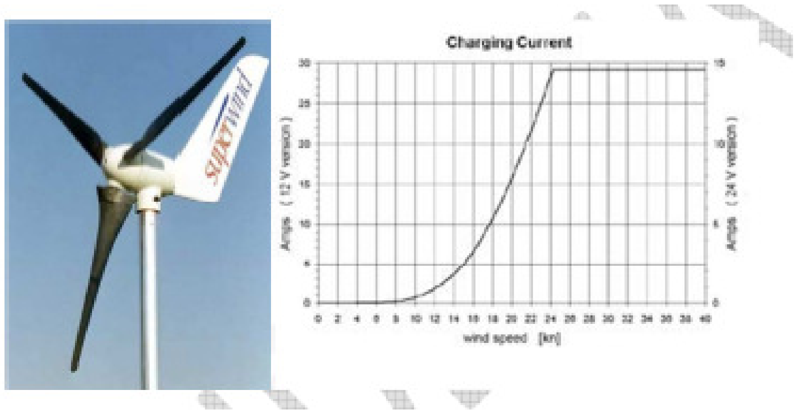

Figure 11 Eolic generator used for BOX with left the wind propeller unit and right the theoretical charging curve as a function of wind speed.

The charging curve shows that above 23 Kn (12 m/s) the current delivered to the battery unit corresponds to about 10% of the nominal charging capacity (240 A h). Practically, very little energy produced above these conditions will be lost. At lower wind speeds, the wind propeller will however not be adequately dimensioned to provide enough current to fully charge the battery unit.

3.2. Battery description

Energy is supplied to the instrumentation through a battery set that also serves as an energy storage system. Ideally, the battery set is dimensioned to allow two full-days of operation (48 h) in case of failure of the energy production unit or in case of external weather conditions that would limit power production by both solar panels and aeolian generator.

A first choice for the batteries was the use of the very classical Pb-gel batteries. With four Pb-Gel batteries which have a total capacity of 240Ah (60Ah each), and a nominal voltage supply of 12.5V, a power of 3000Wh is available. During past experiences, it was found that power supply during 60 hours (2 days and half) without charge from solar panel or aeolian generator can be provided.

The battery control is performed with the following sensors:

- Solar current monitoring the energy production by the solar panel;

- Eolic current monitoring the energy production by the Aeolian generator;

- Batteries voltage that monitors the state of the battery.

Batteries voltage informs about the charge level. Solar and Eolic current informs about current absorbed by the battery. These 3 parameters are the key to decide to switch between different operation modes of the system (normal, energy safety, ...). As mentioned earlier, for ideal conditions of radiation, the current provided by solar panels reaches about 20A.

Pb-gel batteries are quite cheap. However, one of the important limitations of this set up is that each battery has a weight of 20kg leading to a total weight of 80kg. An additional limitation is represented by the rather limited range of operative temperatures. To respond to these limitations, Lithium-ion batteries (LIB) can be used. This is a rechargeable battery type (to be distinguished from the non-rechargeable lithium battery), common for use in small electronics given its high energy densities and slow loss of charge when not in use. Their price used to be problematic for applications requiring larger energy consumption; however their growing popularity for the electric vehicle and aerospace applications is pulling prices down.

For application in transportable monitoring stations, a clear competitive advantage is also weight and functioning under cold conditions. It remains however, a much more expensive solution that will require extra protection, especially in the case the system is left unattended in the field.

The table below compares weight and energy production for two battery sets. A Li-Ion battery can provide 3696Wh for a total weight of 30kg which would require almost 80 kg for the Pb-gel set.

Pb-Gel	**Li-Ion**
80 kg	30 kg
3000 Wh	2696 Wh

Converted into energy densities, Li-Ion can provide 123Wh/kg whereas Pb-Gel can provide 38Wh/kg which is a clear advantage for transport.

4. SAMPLING ENTITY

The sampling entity of the tested system is far from being trivial. Mountain sites required the development of solutions for the efficient sampling of aerosol and gases under adverse meteorological conditions: whole air inlets, capable of sampling the aerosol phase even in cloudy conditions, counter-flow virtual impactors for sampling the activated phase only, interstitial inlets for interstitial aerosol and gas only, etc.. For activities under the PM regulation, PM10 and PM2.5 are regularly used.

Original solutions had to be found that would permit:

- Efficient sampling of particles and gases in clear sky conditions;
- Embedded de-icing device;
- Limited power consumption;
- Control system preventing from sampling if conditions are not suitable (clogging of inlet due to ice formation for example).

Sampling of large drops (>5 μm) should be avoided, first to avoid freezing of drops inside the tubing and, second, to prevent humidity from reaching the instrumentation. Therefore the **whole SAMpling Entity (SAME),** that carries the air to each measurement device, should be properly dimensioned. The SAME unit contains:

- Pumps
- Differential pressure sensors for flow measurements
- Ice sensor
- Inlet Heating system
- Humidity & Temperature sensors

All these systems operate according to a given cycle: pumps are activated when measurement starts. The flow rate of the inlet is checked. If the value is higher than a threshold defined by the differential pressure system, the corresponding flag “Inlet block control” is set and pumps are stopped. A flow limitation is indicative of inlet clogging and instruments must not work at low pressure (in particular the CPC). Otherwise, task waits to be sure the air sampling will be in devices measure chamber. It is a control performed to protect pumps and instruments. This control is also performed during the measurement.

4.1. Architectural diagram

The overall sampling flow chart is shown in Figure 14, including the different instruments installed as core instruments of the BOX.

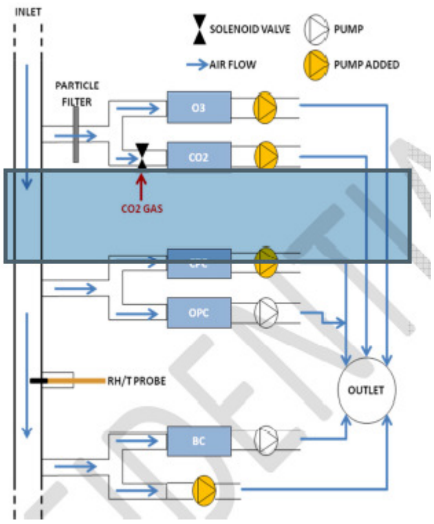

Figure 14 Architecture of SAME. Pneumatic diagram.

The overall sampling system is dimensioned with both internal pumps of the specific instruments and additional pumps to increase flow rate. Only 12V pumps have been used to protect against short-circuit. This implied modification of some instruments (CPC in particular) to adapt to low voltage. Overall the flow through the inlet varies from 1 to 10 l/min depending on the degree of energy saving mode. To control the inlet flow rate and to avoid damaging the pumps (or instruments) when working at low pressure, a Differential Pressure (DP) measure is installed.

4.2. SAME control system

4.2.1. Inlet system

The inlet is made of stainless steel material and has the following characteristics:

- Inlet flow rate 10 l/min allowing for a PM0.8 sampling
- Cover prevents snow to penetrate inside the inlet
- Ice sensor detects formation of ice
- P-T-RH sensor for detecting ice forming conditions
- Vibrator underneath the cover to help removing ice
- Heating system to melt snow and ice

In particular, formation of ice in the inlet system is a problem that all operators sampling in high altitude conditions have to face. In whole air inlets, de-icing is automatically switched on as soon as certain conditions of RH and T are reached, to prevent ice formation. Usually, de-icing systems are dimensioned with several hundreds of Watts which are not a problem when energy resources are available. It is obviously not the case for transportable system in mountain or remote areas. Because the de-icing energy is limited, a suitable strategy is to prevent ice formation by early detection of ice and to switch to full safety mode whenever conditions are not suited for sampling. The ice control system is therefore chosen as an indicator for sampling conditions. For the tested system ,the ice control is based on an optic measure. It is a “NewAvionics Corporation” sensor called “Ice Meister Model 9732-OEM”. This ice detecting probe monitors the opacity and index-of-refraction of the substance which is on the probe.

To prevent ice cap and avoid inlet blocking in ice alert and more ice modes, a heating system is installed on the inlet head. It consists of a heating resistance placed within a stainless steel cover. The heating resistance is coupled to the ice sensor. So it can be decided to activate heating system under specific ice states. The dimension of the resistance is not suited for operation in supercooled clouds. Another problem is linked to re-icing of the melted snow present in the inlet that produces denser ice than the original snow. The inlet is designed to ensure that melted snow/ice will not contribute to additional clogging but the perfect inlet does not exist under these conditions.

An important element in the system is the Relative Humidity & Temperature (RH/T) measurement. This monitoring will be used for quality of scientific data (corrections, sample conditions, ...) but also to evaluate the proper working conditions. It is therefore important that this measurement is performed with good accuracy, trueness and precision (depends of quality and metrology device). To satisfy these constraints, the sensor used is a “Rotronic” probe referenced as “HC2-C05”. This probe is shipped with a calibration certificate.

5. INSTRUMENTATION ENTITY

The system which worked at Askole, was equipped with measurement systems for ozone (O3), carbon dioxide (CO2), number (CPC) and size (OPC) of particles. In parallel a weather station (Vaisala WXT-520) was embedded in the system. A further upgrade, here not tested, is represented by a module for measuring black carbon (BC) concentration.

5.1. Instrument modifications

As mentioned previously, the system is equipped with commercial instrumentation.

O3 Monitor

This instrument has a control on the cell temperature and starts a heating resistance when temperature is below a certain treshold. So for safety energy reason, this resistance is kept disconnected. We therefore only rely upon our temperature control for O3 analysis; As mentioned before, it is very unlikely that temperature in the box goes below this threshold. In addition, the instrument cover is removed to gain some weight.

CO2 Probe

This probe is, per se, small, light and low power consumption. No modification is required prior to installation. However, as for any other CO2 probe, accurate calibration is required. Obviously, the calibration procedure has to be automatically managed. This calibration needs:

- A certified CO2 Gas cylinder (provided by LSCE)

- A Manometer with micro valve (flowrate regulator)

- 3 solenoid valves

Calibration of the CO2 probe is performed every 12 hours.

CPC

The "Condensation Particle Counter" (CPC TSI-3010) is the heaviest and the "warm-up" instruments of the portable system. One first limitation of the CPC concerns its energy consumption when used in its commercial version. In fact, CPC requires 220V alternative input power supply and an external pump. Some modifications are necessary to adapt the CPC power supply to the portable system and an internal pump was added. This included modifying the power requirements to adapt the CPC to a 12V input power supply and to remove all parts that can induce pressure drop and require then a larger pump. In particular, the critical orifice that controls flow rate in a conventional configuration was removed. An important issue is that modifications performed to this CPC 3010 cannot be directly transferred to the new generation of TSI CPCs.

Operation requires buthanol as a condensing fluid. The buthanol consumption depends on working conditions but typically, the external reservoir (capacity of 250 mL) will allow for just a few days of operation. Typical buthanol consumption is indicated in the table below (for 1L of buthanol):

Running time	Duration
Continuous	1 week
15 min/h	1 month

With an intermittent running time of 15min/hour, the CPC can operate up to 4 months. The buthanol reservoir was placed in the "utility box": this required an additional filling system since the CPC in normal use has its reservoir placed on its top and is filled by gravity.

A second consideration relates to the Peltier cooling system that permits particle condensational growth by thermal gradient but that consumes a high level of energy that prevents a continuous use in normal operations. For these reasons, the CPC cannot be used in continuous mode but has to switch from energy saving to operations. This switch has to be based upon the charging conditions of the batteries.

OPC

The "Optical Particle Counter" (OPC, Grimm 1108) works independently and the interval to get data is defined by user. OPC performed a series of internal tests during its working operations. Because the flow is now controlled by the system itself, a modification was performed to bypass the self control of the OPC.

Weather trasmitter

The weather trasmitter (Vaisala WXT520) is fixed to the system by a stainless steel tube. This station allows knowing weather conditions of the environment:

- Temperature, Humidity, Pressure
- Wind speed and direction
- Rain intensity, duration and accumulation

Apart from the information itself that are required for data interpretation, knowledge of these parameters is also important for comparing internal and external conditions. This is also important for the internal control for example to activate temperature regulation in the box. The weather station is also equipped with a heating system that allows working under rough conditions (high winds, low temperatures and high relative humidity).

BC Analyzer

A micro-aethalometer based on measuring the rate of change in absorption of transmitted light due to continuous collection of aerosol deposit on filter can be implemented in this transportable system. Measurement at 880 nm is interpreted as concentration of Black Carbon ('BC') assuming a certain mass absorption coefficient.

This "*microAeth*" is designed to work independently in continuous mode during 1 month without filter change. Under normal conditions, the filter has to be changed manually every day which does not make it a suitable instrument for an autonomous station meant to operate unattended for months. However, for very low concentration (such as those expected at high altitude remote areas), one filter may be sufficient for monitoring for up to 2 months.

5.2. Data collection

Data from all instruments are all centralized and processed along similar stream flows. An electronic and serial interface allows collecting all instruments data by serial communication (RS232 protocol). Instruments data contains *"variable measured"* and *"instrument working parameters"* data in order to remotely control the proper functioning of all instruments and possibly identify causes for malfunctioning before manual check in the field. All data are saved on microSD as sensor data.

6. SYSTEM CONTROL ENTITY

The **SYstem Control Entity (SYCE)** contains all electronics components and sensors necessary for the monitoring operation: it controls instruments, sensors, data acquisition and transmission. It is therefore essential that the SYCE is built with a high degree of quality and be reliable for unmanned operations in the field.

SYCE ensures the following functions:

- Scientific instrument operations
- Scientific instrument data collection
- Sensors data collection
- Data saving
- Data remote communication (out)
- Power management
- Real time CO2 calibration
- Instrument protection
- Station working report

7. DATA REMOTE COMMUNICATION

The system can send wireless data by two ways:

- Radio Modem
- Satellite Modem

The radio modem (SATEL, model SATELLINE-3AS) can send data at a distance of about 10km. The wireless communication and RF protocol is fully supported by the modem, and the uC communicates with a serial RS232 protocol. All the data can easily sent. It is used if there is a radio modem network, or a station with an internet connection at a distance of less than 10km.

The satellite modem is an Iridium modem. It is a very small package and very low power consumption. It supports Short Burst Data (SBD) messages. This modem is used if the station is in a really remote area without anything in a radius of 10km. The SBOX sends small data messages with the state of the station.

8. CONCLUSIONS

From a technological development point of view, this BOX has responded more than satisfactorily to the difficult operative conditions:

- the design of a box is isolated from temperature variations and external adverse weather conditions;
- good adaptation of the instruments and sensors to adverse weather mountain conditions; some problems observed during very cool condition;
- production of energy and efficient storing units able to maintain their autonomy.
- the system can be implemented and adapted for monitoring other parameters

In spite of some problems with respect to specific components (the CPC stopped after 32 days from the activation and the OPC was not active), the results of the measurement campaign on Karakorum, confirmed that this transportable system can be effectively used in remote areas that are otherwise difficult to sample.

The good results obtained can certainly be considered a success and form the basis for any subsequent system upgrades.