Design and Development

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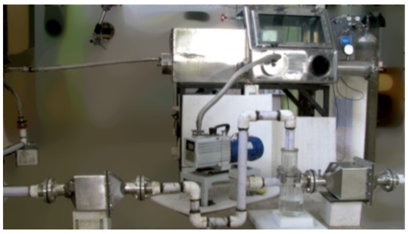
A Passive Bi-directional Safety Relief Valve for Nuclear Applications

Nagaraj Alangi*, Mukesh Kumar Verma, Dev Ranjan Das, Soumitra Kundu and Sanjay Sethi

Advanced Tunable Laser Applications Division, Beam Technology Development Group, Bhabha Atomic Research Centre, Trombay – 400085, INDIA



SRV proof of concept setup

ABSTRACT

Inert atmosphere glove boxes with attached glove ports typically of 200 mm and 160 mm diameter are extensively used for handling toxic and radioactive materials. Pressure regulating valves are conventionally used and beyond its specified limits regulation of the glove box pressure may be compromised. In this work, we report design, development and testing of a passive, compact, prototype safety relief valve (SRV) with silicone oil as bubbler fluid to mange the glove box pressure, both in dynamic as well as in the isolated condition. The onset of the relief and the transient glove box pressure were measured as a function of flow in the range of 0-60 lpm and always found to be at 12.5 mm ±1 mm water column (WC). The glove box when evacuated using rotary pump with nominal pumping speed of 16 m^3/h reached a maximum negative pressure of 177 mm of WC, which was within the desired safety limit. During its extensive testing, the SRV functioned at the set boundaries with the desired sensitivity and proves its application in the safe glove box operations.

KEYWORDS: *Prototype safety relief valve, Engineered safety feature, Glove box safety*

Introduction

Bhabha Atomic Research Centre (BARC) utilizes a number of inert atmosphere glove boxes with attached glove ports typically of 200 mm and 160 mm diameter, and which house toxic and radioactive materials [1-6]. Several operations are undertaken in the equipment housed in the glove boxes such as vacuum treatment, annealing, sintering, attrition, melting etc. Generally, the ventilation system in the glove boxes is once through type in which an inert gas is flowed in the glove box through the gas inlet line and discharged into the exhaust line which drives to the stack after passing through various stages of HEPA filters. In practice, the radioactive material is handled in the glove box at -25 mm water column (WC) ±12.5 mm WC pressure (negative guage pressure) and the dynamic negative pressure is maintained in the glove box using a pressure regulating valve (PRV) installed on the exhaust side of the glove box. The pre installation setting of the PRV is done for a specified pressure and flow of the exhaust system to maintain -25 mm WC and regulate the glove box pressure within ±2.5 mm WC accuracy. Beyond the specified limits of exhaust line pressure and gas flow, regulation of the glove box pressure may be compromised. Similarly, when the glove box is isolated by closing the inlet and outlet valves as is the normal practice, PRV cannot regulate the pressure in the glove box.

There are a number of scenarios in which the glove box is either over pressurised or under pressurised from the nominal operation conditions. An isolated glove box can be over pressurized due to increase in the glove box temperature, inadvertent leak of any pneumatic line inside the glove box, heat/gas released due to chemical reaction and malfunction of the inlet gas cut-off valve. Under-pressurization of an isolated glove box can be due to a leak in any of the vacuum boundaries of the equipment housed in the glove box. Similarly, under-pressurisation of the glove box can also be witnessed in a ventilated glove box when the flow due to leak in the vacuum boundary is more than the inlet gas flow. An extreme condition of glove box can result when the vacuum pump is directly evacuating glove box due to a catastrophic failure of a component.

In the glove box, the gloves denote a hazard, in that they could get detached if the glove box were accidentally over pressurised or under pressurised thereby releasing radiotoxic material to the laboratory environment. Beyond the pressure gradient design limits of the glove box panel, the panel may crack, break or develop leak, thereby release the radiotoxic material to the laboratory environment. In some laboratories, as a precautionary measure the glove boxes are fitted with active pressure relief devices which will vent into a dedicated exhaust system and not into the laboratory [7]. The pressure relief setting is generally set to limit the difference between the glove box pressure and barometric pressure in the laboratory, since it is this pressure difference which causes the gloves to detachment. Dedicated passive over pressure relief devices for glove box are reported by several groups based on bubbler devices using suitable liquid [8,9,10].

Active pressure relief devices are available for the wide range of the requirements, but they stop functioning in the event of a station blackout condition, which is undesirable. Spring loaded relief valves are available for the wide ranges of pressure, which are extensively used for high pressure applications, however at near atmospheric ranges these spring-loaded valves are not thoroughly reliable. Mercury bubblers are widely used in different laboratories to relieve the over pressure of glove box by bubbling through mercury and the set-point set by the hydrostatic head. Several designs of check valves are reported for mercury bubblers to isolate the glove box [9]. Rupture disk type of safety relief valves are not an option for laboratories handling toxic and radioactive

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*Author for Correspondence: Nagaraj Alangi
E-mail: nagaraj@barc.gov.in

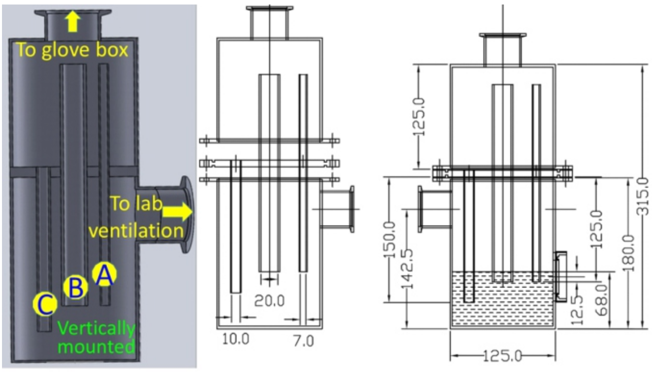

Fig.1: Engineering drawing of bi-directional safety relief valve.

materials. There is no reported literature available on the safety relief valve which is functional both during over pressure and under pressure.

Engineered safety features for glove box are designed to protect the worker from hazards. Eliminating the hazards is the preferred control; however, a hierarchy of controls are being used to implement feasible and effective controls. Protection of the worker is dependent on active and passive controls, good work practices, training, ergonomic consideration, and housekeeping. Hence to mitigate the hazard of glove detachment, the need is for a device which functions as a passive pressure relief device and is sensitive to room barometric pressure, but not the downstream pressure in the exhaust line. The same device shall also function as a passive check valve to limit glove box pressure within the specified range. This forms the motivation for this developmental work.

In this work, we report the design, development and testing of a passive, compact, prototype safety relief valve (SRV) with silicone oil as bubbler fluid to limit the glove box pressure, specifically when the glove box is in an isolated condition. This SRV proposed is a passive device with no mechanical components and the device can function at both positive and negative set pressure boundaries.

Design Considerations and Functionality

Description and functionality

The bidirectional safety relief valve essentially contains two cylindrical compartments one above other, connected with three tubes of different sizes (tube A, B and C), each tube serves a different functional requirement. Fig.1 shows the drawing of the SRV. The top cylindrical compartment is connected to the glove box and the bottom compartment is connected to piping exposed to the laboratory exhaust. The connections of both the cylindrical compartments to respective piping's are O-ring based quick connect fittings for ease of maintenance. A viewing window in the SRV serves to monitor the fluid level. Tubes A and B are immersed in the silicone oil contained in the bottom cylindrical chamber. In the normal conditions, the immersion of these tubes in silicone oil isolates the glove box from the ambient atmosphere. The schematic of the layout of the SRV for implementation in the actual application is as show in Fig.2. The HEPA filters prevent the release of toxic particulates from glove box to the ambient atmosphere. The U bend in the pipe line serves as an accumulator for any oil droplets carried away by the air ingress to the glove box under extreme under pressurisation.

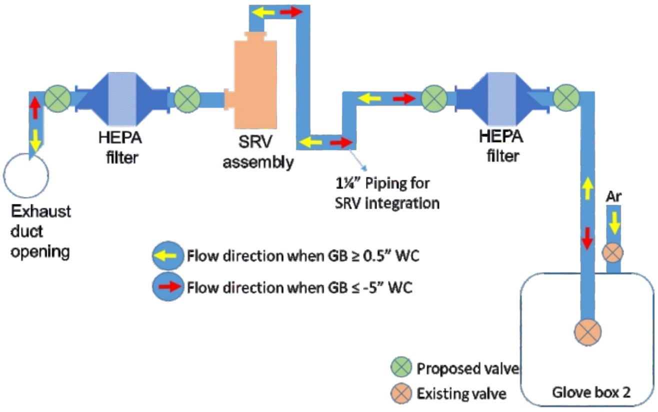

Fig.2: Schematic of the layout of the SRV for implementation.

The over-pressure relief of glove box is obtained by the submerged vent line (tube A) in a silicone oil reservoir, the relief pressure being a function of the submerged depth and is maintained at 12.5 mm. The choice of the bubble fluid is detailed in the selection of materials section. The gas released is filtered through HEPA filters, one placed before the SRV and another after the SRV in the piping layout. The type of gas (Ar, N_2, He or air) was not having strong influence on the release pressure [9]. Initially when the over pressurization is relatively less, bubbling happens through the tube A, which is favourable for bubble formation owing to its smaller size. However, if the flow of gas causing over pressurization is more, both tubes A and B will participate in the venting.

In the event of under-pressurisation of the glove box, all the three tubes commence sucking of oil into the tube. Eventually, there comes a point at which the oil level has reached below level of tubes A and B, there by exposing the cross-sectional area of both the tubes A and B. At this point, the fall of oil plug in the tube due to gravity is balanced by the opposing force of vacuum in the glove box. When the glove box is further under-pressurized, the oil plug moves up and enters in to the top cylindrical chamber. At this point, the tubes are clear of oil and allow air into the glove box. The oil from the top cylindrical chamber is returned to the bottom cylindrical chamber through tube C. At a given flow of air, which is a function of the under pressurization, there is a dynamic balance between the suction of the oil through the tube A and B and return of oil via tube C. The maximum negative pressure perceived by the glove box in the event of under pressurization is a strong function of the air flow into glove box. At a given sizing of pipe and route, the pressure drop across all the elements decide the maximum flow achieved.

Hence, the peak negative pressure perceived by glove box is directly related to the extent of under pressurization and air flow rate achievable. The onset of the under-pressure relief of glove box is a function of the total volume of the fluid sucked through all the vent tubes, which clears the vent lines A and B for air inrush.

__Design and sizing considerations__

- It should be compact and light weight and sufficiently protected for avoiding any damage due to mild external impact.
- The piping size shall be chosen to achieve the desired flow of air/gas with acceptable pressure drop across all the components.
- The fluid used in the SRV should not result in more than 1 ppm concentration of its vapour in the glove box during normal operation of glove box.

- A provision shall be available to measure/monitor the fluid level in the SRV, there by quantity of the fluid.
- The SRV module should have replaceable HEPA filters at both the ends to be connected to glove box and the vent line respectively.
- Mist eliminator should be provided between the HEPA filter and fluid line/container of the SRV to avoid its blocking of HEPA filters.
- Provision shall be available to monitor health of SRV system by periodic testing of its performance for onset of release of excess positive & negative pressure, rate of release of pressure.
- All the connections and joints shall be 'O' ring based with quick connect fittings for ease of handling and convenience in achieving suitable leak tightness.

Limits of operation

The SRV is to be meant for relief of excess positive or excess negative pressure in the glove box directly to the exhaust duct of room ventilation. The onset of release of excess positive pressure of glove box only shall be at +12 mm WC ±2 mm WC and release of excess negative pressure of glove box shall occur at −125 mm WC ±5 mm WC. The SRV shall maintain a seal to prevent exit/entry of air in between +12.5 mm WC and −125 mm WC of glove box pressure. The rate of release of excess positive pressure in the glove box should be ≥60 lpm with glove box at 25 mm ±2 mm WC. This scenario is envisaged under the conditions of failure of regulation by PRV and inert gas flow solenoid valve is malfunctioning. Similarly, the rate of release of excess negative pressure in the glove box should be more than 200 lpm with glove box maintained at -180 mm ±5 mm WC. This extreme flow is observed when there is a breach of vacuum seal or catastrophic failure of glass window attached to vacuum chamber either in the dynamic pumping or isolated condition.

Selection of materials for SRV

The fluid used in the SRV plays a major role in the performance of the SRV to have no contamination to the associated glove box. Ideally, the SRV fluid should be radiation resistant, oxidation resistant, explosion resistant, chemically inert, minimum combustion hazard, have low vapour pressure, recyclable, extended life without degradation of properties, less viscous and non-wetting. Water is generally used in many bubblers; however, it has the disadvantage of high vapour pressure thereby increasing the moisture concentration in the inert glove box. Mercury is also used in SRV for glove box, however not considered in the current study as it may not provide greater resolution and also lead to severe health hazards. Hydrocarbon oils are not considered due to their flammability and high vapour pressure. Hence the obvious choice is the silicone-based fluids; specifically, the phenyl methyl-siloxane (DC 702), tetramethyl tetraphenyl trisiloxane (DC 704) and pentaphenyl trimethyl trisiloxane (DC 705) fluids which have very low vapour pressure at room temperature and are stable over longer duration of time. Out of the listed silicone-based fluids, DC 704 was chosen keeping in view of its vapour pressure, availability, stability, cost and vast experience in handling the fluid in the vacuum generation systems. Some indication of the holdup of oil in the steel components was derived from the experience of diffusion pump before finalizing the fluid for SRV. Table 1 shows properties of silicone based fluids.

Table 1: Physical properties of silicone based fluids.

S.No	Specifications	DC 702	DC 704	DC 705
1	Vapor Pressure at 25°C (torr)	$1x10^{-6}$	$1x10^{-7}$	$1x10^{-9}$
2	Boiling Point at .5 torr (°C)	180	215	245
3	Viscosity at 25°C (cSt)	45	39	175
4	Flash Point (°C)	193	221	243
5	Density at 25°C (g /ml)	1.07	1.07	1.09

The materials used for fabrication of the SRV have several considerations such as transparency, fabrication ease, surface condition, radiation resistance, amenable to coating, compatibility with both SRV fluid and the ambient air and SRV fluid hold up. One of the important considerations is the SRV fluid holdup which decides on the extent of the fluid participating in the SRV functionality. If the holdup of oil is more on the internal walls of the SRV, the onset of relief in both over pressurisation and under pressurisation occurs earlier than the designed value. Hence, careful selection of materials is necessary to have reliable functionality of the SRV. Transparent materials such as quartz, glass and Perspex were not considered for the construction of SRV as they are likely to be damaged due to mild impact; however, quartz window with suitable protection is used as a fluid level indicator (level sensor was not chosen considering passive design). In this study, SS304 has been chosen as the material of construction of the SRV due to ease in fabrication and availability. Based on the separate study of the contact angle of silicone fluids with different materials, a suitable coating of Teflon is proposed on all the internal surfaces of SRV for minimal holdup of SRV fluid.

Instrumentation requirements

The SRV shall be supported by reliable instrumentation for different aspects. Instruments are required for measuring and transmitting the glove box pressure and temperature, detect the onset of the SRV and generate an alarm, measure and transmit the pressure drop across the HEPA filter during flow conditions and flow measurement during testing conditions. The Magnehelic gauge being the industry standard to measure pressure drop across HEPA filters are used to determine choking of HEPA filter. Pressure transmitters for both under and over pressurisation are connected to glove box to measure and transmit the real time data. RTD based temperature transmitter is used to measure the temperature of the glove box. A high-speed data logger records all the data transmitted by the instruments for the presentation of historical trends and observation of transients during testing.

Periodic testing method

A dedicated arrangement for period testing of SRV is necessary to test the reliability and efficacy of the SRV. The schematic of the layout for periodic testing is as shown in Fig.3. A dedicated testing line branching from the SRV line is connected to the glove box exhaust through a HEPA Filter for testing the SRV for relief from under pressurization. For testing the SRV in over pressurization, a gas line is connected to pipe after the first HEPA filter as shown in the layout. Any makeup of the SRV fluid can be done by opening the 6.4 mm compression fitting in the lower cylindrical compartment.

Experimental testing and validation

The SRV was tested extensively in multiple stages of development. Initially the proof of concept was demonstrated using an SRV fabricated out of Perspex to witness the

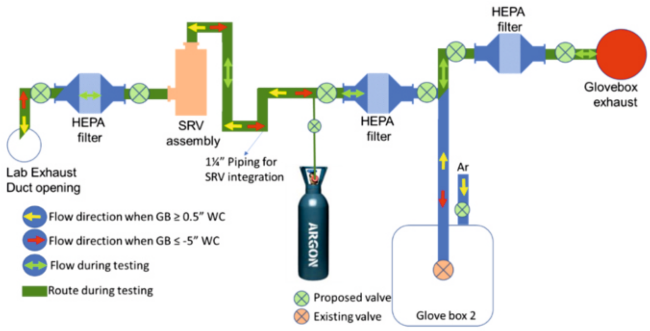

Fig.3: Schematic of the layout for periodic testing of the SRV.

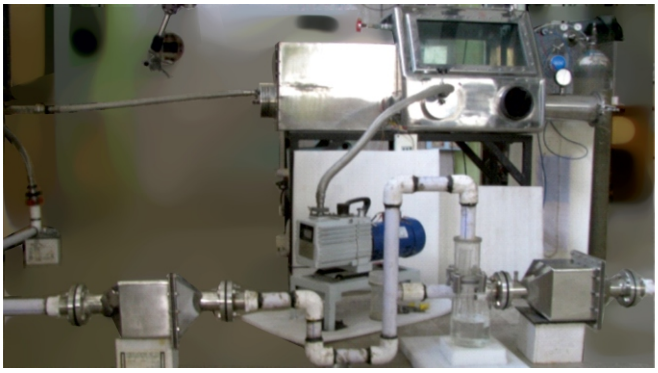

Fig.4: Photograph of the SRV proof of concept setup.

activation of SRV at both the set pressure boundaries and water was used as the SRV fluid. The proof-of-concept set-up of the SRV is shown in Fig.4 in which the top cylindrical portion of SRV was connected with an inactive test glove box using 1¼" PVC piping along with the HEPA filters and bottom cylindrical portion of the SRV was kept open to atmosphere via HEPA. Argon gas was used to create positive pressure in the glove box and 8 m^3/h rotary pump with a control valve was used to generate negative pressure in the glove box. A photohelic gauge (0-4" WC) was used to precisely measure and control the positive pressure of the glove box and a water manometer with ±1.0 mm WC accuracy was used for measurement of absolute pressure in the glove box.

Subsequent to the demonstration of the proof of concept, a SRV made of SS304 was fabricated with the design dimensions and the piping with HEPA filters was retained for testing. The schematic of the layout for testing is as shown in Fig.5. A rotary pump of 16 m^3/h was used to evacuate the glove box of 1 m^3 volume and argon gas was used to pressurise the glove box. The glove box had all the necessary pressure transmitters connected to a data logger for recording of the glove box pressure during the entire period of testing.

The pipeline length, elbows, HEPA filters were chosen based on the envisaged site layout requirement and PVC pipes of same dimensions were used for testing. Flow of over pressurization gas was measured using a rotameter and flow during under pressurisation was measured at the exhaust of the rotary pump using an anemometer. The value of flow calculated for each reading was an average of at least 5 readings recorded during the testing. A water manometer with ±1.0 mm WC accuracy was used for measurement of guage pressure in the glove box supplemented by the Magnehelic guage mounted on the glove box.

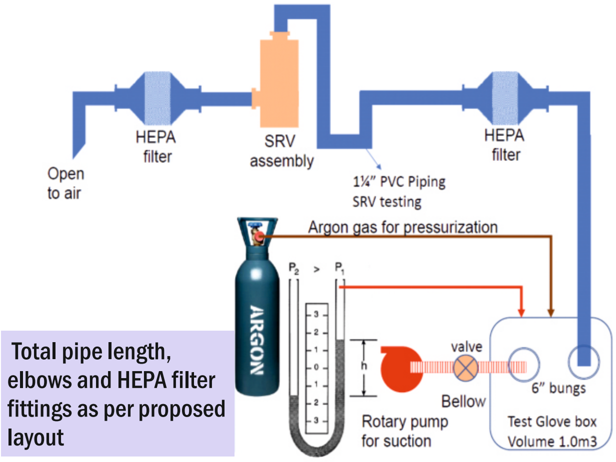

Fig.5: Schematic of the layout for testing of SRV.

Results and Discussions

The bidirectional passive SRV uses the barometric pressure in the laboratory as a reference for the relief pressure and remains unaffected by the pressure fluctuations of the glove box exhaust system. The SRV was tested by connecting to a test glove box which was having a leak tightness of 0.05 volume %/h and volume of 1000 L. Four gauntlets were also used on the glove ports to check for any glove detachment during extreme pressure conditions within the testing limit. The developed SRV assembly must function during the three following different states of the glove box conditions.

The Glove box at nominal operating pressure

Glove boxes are generally evacuated as normal procedure when establishing an inert atmosphere inside and maintained at a pressure slightly below the barometric pressure in the laboratory. The SRV assembly must therefore act as an isolation valve, and not allow flow into the glove box under this circumstance. This functionality is accomplished by the tubes immersed in the silicone oil. When the glove box is slightly (-1" WC) below the barometric pressure in the laboratory, the silicone oil rises up the tubes until the balance of suction and gravity is established without any further rise of oil up the column. Small oscillations occurring due to the operations in the glove box are accommodated by the slight oscillations of oil level of oil in the tubes of SRV and isolation is always maintained.

Glove box venting under over pressurisation

Should the pressure rise in the glove box, the silicone oil in the tubes of SRV is displaced into the cylindrical reservoir until the pressure is not sufficient to generate a bubble. When the over pressurisation continues in the glove box and the flow is low, all the oil in the tubes is displaced until it reaches the bottom of the tube. At this condition, any further flow leads to escape of the gas from the glove box and will rise up through the oil leading to the laboratory exhaust system. This bubble formation happens preferably at tube A as it has the most favourable tube diameter for bubble formation. The setting of the relief pressure is determined by the depth of tube immersed below the level of the silicone oil, in this case 12.5 mm. The onset of the relief and the transient glove box pressure was measured as a function of flow in the range of 0-60 lpm. In the range of the study with DC704 as bubbler fluid, the onset of relief was always found to be at 12.5 mm ±1 mm WC. The glove box pressure monotonously increased with increase in the over pressurisation flow and reached a maximum of 24 mm WC at 60 lpm and continued to maintain at that flow as shown in Fig.6.

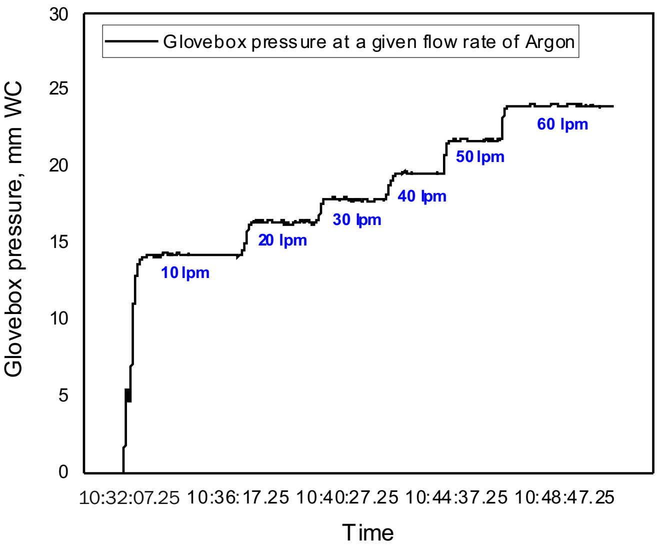

Fig.6: Glove-box pressure at different flow rates under over-pressurization condition.

Argon, helium and nitrogen were used to pressurize the glove box to study the effect of gas. No significant difference was observed either on the onset of relief or the peak positive pressure as anticipated. It should be noted that all the tests were done by pressurization of an isolated glove box, and in a ventilated glove box the pressure is regulated by the PRV and it may never be over pressurised.

Glove box under vacuum

Glove boxes are evacuated as normal procedure when establishing an inert atmosphere inside and the suction is regulated by the PRV. When a glove box envelops a vacuum chamber, which is under dynamic vacuum, the leak or failure will lead to evacuation of glove box limited by the capacity of the rotary pumping system. As the evacuation of the glove box by the rotary pump can lead to more under pressurisation than leak in an isolated chamber, this scenario was chosen for testing of SRV. Table 2 shows the results from the testing of the SRV in which the onset of the relief and the maximum pressure during under-pressurization are tabulated with respect to flow obtained with the different sized fittings used to connect the rotary pump and a glovebox of 600 L.

As can be seen from the Table 2, when a glovebox is evacuated by rotary pump of 16 m^3/h through a 3/8" valve, the flow was relatively less due to the pressure drop across the valve. When the valve was replaced with a quick fitting opening with 22 mm diameter clear opening, the flow increased. When both the connections to glovebox (SRV and rotary pump) were replaced with quick fitting opening with 22 mm diameter, maximum flow of 13.3m^3/h was achieved with a nominal rotary pump speed of 16 m^3/h. It can be observed that the onset of relief during under pressurization was similar in all the tests.

Table 2: Glovebox pressure maintained during the testing of SRV.

Measured velocity, m/s	Calculated flow, m^3/h	Onset of flow, mm	Glove box pressure, mm of H_2O (600L volume)	End connections of piping
3.9	6.9	-125 mm±5mm	130 mm±2mm	3/8" valve
6.3	11.1	-125 mm±5mm	130 mm±2mm	One 22 mm Diameter pipe
7.5	13.3	-125 mm±5mm	185 mm±2mm	Two 22 mm Diameter pipe

However, the glovebox pressure was more negative when the flow was higher for obvious reasons. The major pressure drop occurs at the HEPA filters and the SRV assembly, contribution to the pressure drop from other segments of pipe is negligible.

The test was repeated with a 1000 litre glove box with a data logger to collect 8 data points per second. The variation of the glove box pressure with time when evacuated using rotary pump with nominal pumping speed of 16m^3/h is as shown in Fig.7. The maximum negative pressure of glove box was 177mm of WC. When the test was repeated after duration of ~600 sec, the maximum negative pressure of glove box was 197mm of WC with the same rotary pump. The reason for this behaviour is attributed to the time required for the oil to totally drain back to the reservoir, whose level regulates the dynamic sealing during the air inrush. The test when repeated after a period of 24h again for few minute resulted in a maximum negative pressure of glove box was 177 mm of WC as shown in Fig.8 which confirms the hypothesis. Although the testing at different times, the glove box pressure never reduced below 180 mm WC except when repeated immediately.

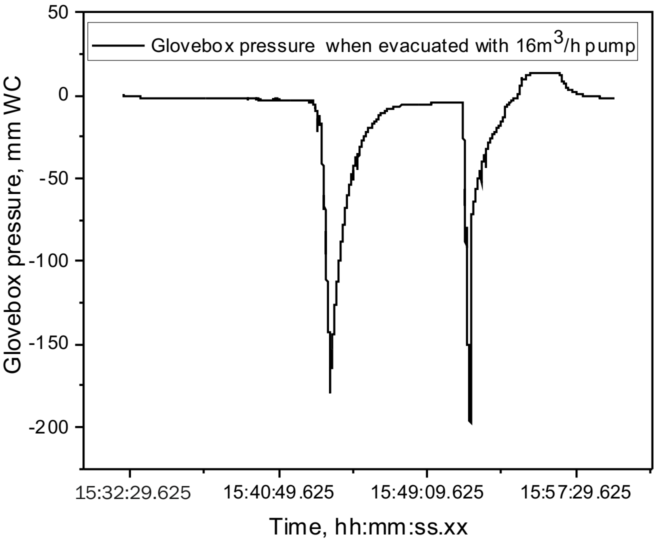

Fig.7: Glove box pressure during under-pressurization by rotary pump evacuation.

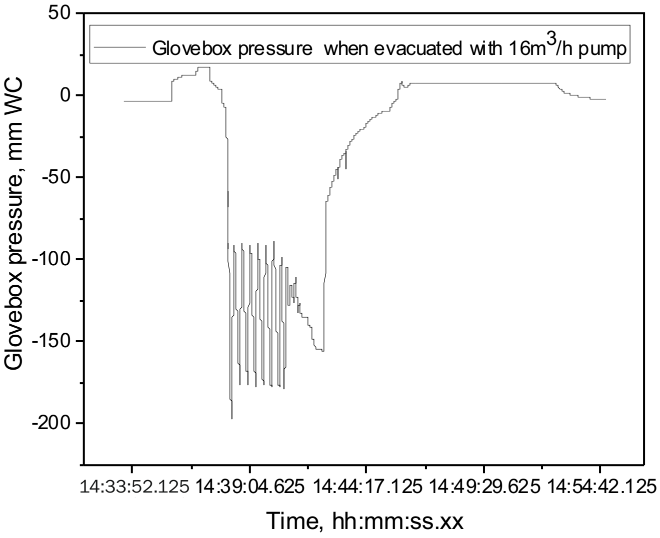

Fig.8: Glove box pressure during under-pressurization by rotary pump evacuation after 24h of previous test.

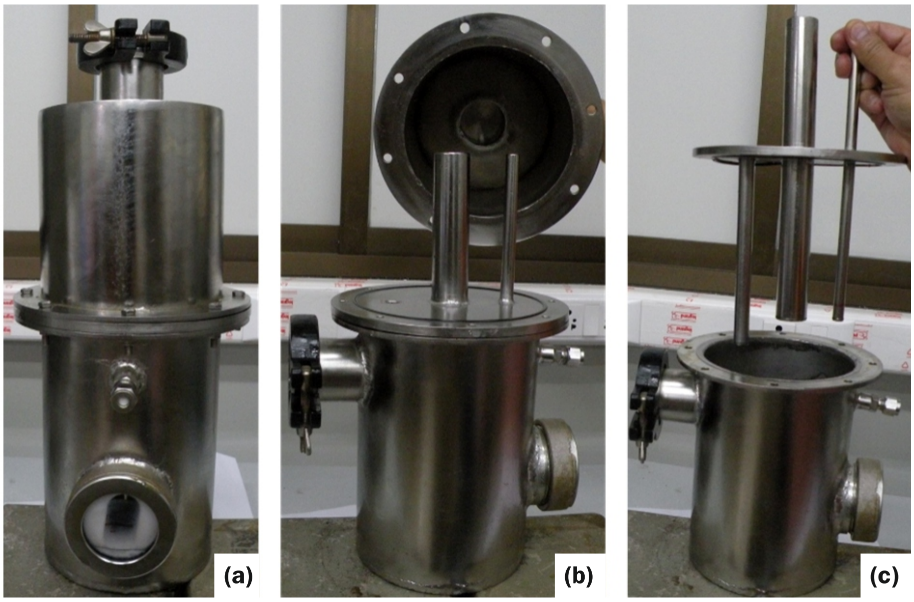

Fig.9: (a) SRV in assembled condition (b) SRV with top cylindrical section open (c) SRV with bottom cylindrical section and the plate with tubes.

Consecutive activation of SRV is not envisaged in actual scenarios as an alarm is generated for human intervention. When the rotary pump was turned off, the glove box pressure reached around 125 mm which is the onset limit. The test was repeated several times to check the reliability and functional limits, and the onset and the maximum negative pressure was within the limits observed. The photographs of the prototype SRV are as shown in Fig.9.

Conclusions

A passive bidirectional SRV has been designed, fabricated and tested for its functionality and found to function suitably for both over pressurisation and under pressurisation of the glove box. During its extensive testing, the SRV functioned at the set boundaries with the desired sensitivity. Its compact design and passive nature have proven its expediency in the safe glove box operations. This SRV also demonstrates the capability of having the glove box, if required without human presence over an extended duration of time. This SRV designed finds application in all glove boxes with nominal operating pressure above or below the atmospheric pressure, and tailoring of oil level is necessary to set the activation limits.

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