

Design and Development of a Prototype Venturi Vacuum System for a Hospital Medical Gas Plant

Diseño y Desarrollo de un Prototipo de Sistema de Vacío por Venturi para una Central de Gases Medicinales Hospitalarios

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ABSTRACT

This study presents the design and development of a vacuum system based on the Venturi effect for hospital medical gas centers. The developed system employs a 3/4" (20 mm) Venturi Mazzei injector with an 8,8 mm throat, driven by a Truper BQAP-1/2-250 pump with a maximum capacity of 45 L/min to generate the required flow rate. System monitoring is carried out using MPX2200GP sensors for pressure, FS300A for flow, and a level sensor, all managed by an ESP32 microcontroller. The acquired data is transmitted in real time via the MQTT protocol to a remote server with a dedicated web interface for monitoring and control. The results indicate that this system represents a viable and cost-effective alternative to conventional methods, providing an efficient solution with lower operational and maintenance costs.

Keywords: Flow; Pressure; Medical Vacuum; Venturi.

RESUMEN

Este estudio presenta el diseño y el desarrollo de un sistema de vacío basado en el efecto Venturi para centros de gases medicinales hospitalarios. El sistema desarrollado utiliza un inyector Venturi Mazzei de 3/4" (20 mm) con una garganta de 8,8 mm, accionado por una bomba Truper BQAP-1/2-250 con una capacidad máxima de 45 l/min para generar el caudal requerido. La monitorización del sistema se lleva a cabo mediante sensores MPX2200GP para la presión, FS300A para el caudal y un sensor de nivel, todos ellos gestionados por un microcontrolador ESP32. Los datos adquiridos se transmiten en tiempo real a través del protocolo MQTT a un servidor remoto con una interfaz web dedicada para la monitorización y el control. Los resultados indican que este sistema representa una alternativa viable y rentable a los métodos convencionales, proporcionando una solución eficiente con menores costes operativos y de mantenimiento.

Palabras clave: Flujo; Presión; Vacío Medicinal; Venturi.

INTRODUCTION

Medical vacuum plays a fundamental role in various clinical procedures, including surgical interventions, respiratory therapy, and fluid suction.^(1,2,3,4,5,6,7,8,9) Traditional solutions, such as liquid ring vacuum pumps, involve high acquisition costs, high energy consumption, and ongoing maintenance.^(10,11,12,13,14,15,16,17,18) This work presents a proposal based on the Venturi effect, providing an innovative, economical, and efficient method for generating medical vacuums in hospitals.

Medical vacuum is essential in modern healthcare infrastructure,^(19,20,21,22) especially in hospitals,^(23,24,25,26) where it is used in various clinical applications, such as surgery, respiratory therapy, and fluid aspiration procedures.^(27,28,29,30) In these contexts, conventional solutions, such as electric pumps or liquid ring systems, pose significant challenges because of their high operating costs, considerable energy consumption, and constant need for preventive and corrective maintenance.⁽¹⁾

In response to these technical and economic limitations, this study focuses on an alternative based on the Venturi effect.^(31,32,33,34) The Venturi effect utilizes fundamental principles of fluid dynamics to generate vacuum by decreasing fluid pressure as its velocity increases in a narrow section of the tube.^(35,36,37) This technique allows for a significant reduction in maintenance and operating costs because of the absence of moving parts and reduced system wear.⁽²⁾

Furthermore, the integration of advanced sensors for real-time remote monitoring provides substantial improvements in system oversight, increasing efficiency and enabling more effective predictive maintenance.^(38,39,40) This approach not only reduces costs but also enhances the safety and reliability of the overall system, thereby ensuring consistent and safe performance in sensitive medical applications.^(41,42,43)

DEVELOPMENT

Principle of operation

The proposed system utilizes the Venturi effect, described by Bernoulli's equation. This equation states that, in an incompressible flow, the sum of the static pressure, dynamic pressure, and potential pressure remains constant along any streamline:⁽³⁾

$$P + 1/2(\rho v^2) + \rho gh = \text{constante} \quad (1)$$

where:

P is the fluid pressure.

ρ is the density of the fluid.

v is the fluid velocity.

g is the acceleration due to gravity.

h is the height of the fluid relative to a reference point.

As the fluid passes through a narrow section, its velocity increases, resulting in a reduction in pressure and the generation of a vacuum.

According to,⁽⁴⁾ the equation can be expressed as follows:

$$P_1 + 1/2(\rho v_1^2) + \rho gh_1 = P_2 + 1/2(\rho v_2^2) + \rho gh_2 \quad (2)$$

In accordance with the continuity equation,⁽⁵⁾ mass conservation can be mathematically represented as follows:

$$A_1 \times v_1 = A_2 \times v_2 \quad (3)$$

These equations allow us to analyze the behavior of the fluid in the Venturi system and establish the relationships among the pressure, velocity, and flow rate in each section of the duct. Applying the principle of continuity to Bernoulli's (2) equation (3) yields the following:

$$P_1 + 1/2(\rho v_1^2) = P_2 + 1/2(\rho v_2^2) \quad (4)$$

Hardware development

The hardware of the system was developed on a printed circuit board (PCB) designed using Proteus software (figures 1 and 2). The electronic components were selected with the aim of ensuring the system's efficiency and accuracy.

Power and Control Circuit

The power circuit provides the specific, stable voltages required for the proper operation of the prototype's sensors and actuators. This circuit consists of the following components.

- 220 V AC to 12 V AC transformer.
- L7805 voltage regulator to power the ESP32 microcontroller.
- L7808 and L7908 regulators to power the AD620 instrumentation amplifier and the AO741 operational amplifier.
- L7810 regulator to power the MPX2200GP pressure sensor.

The control board includes a connection to an SSR-25 solid-state relay used to safely control the activation and deactivation of the

water pump and solenoid valves. AD620 and UA741 operational amplifiers were used to amplify the signal from the MPX2200GP pressure sensor. The system also processes readings from the level sensor and flow sensor, all of which are managed by the ESP32.

The MPX2200GP pressure sensor monitored the generated negative pressure, while a vacuum gauge connected to the system displayed the values in kilopascals directly on the control panel. The FS300A flow sensor, capable of measuring up to 60 L/min, operates within the ideal range for monitoring water flow through the Venturi. The level sensor constantly monitored the amount of water available in the reservoir.

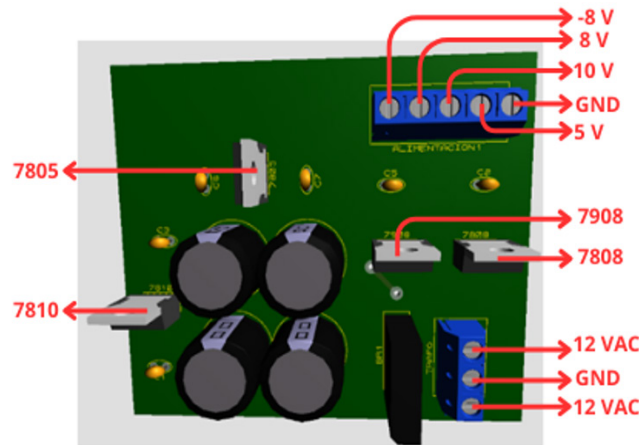


Figure 1. Development of the Source Board

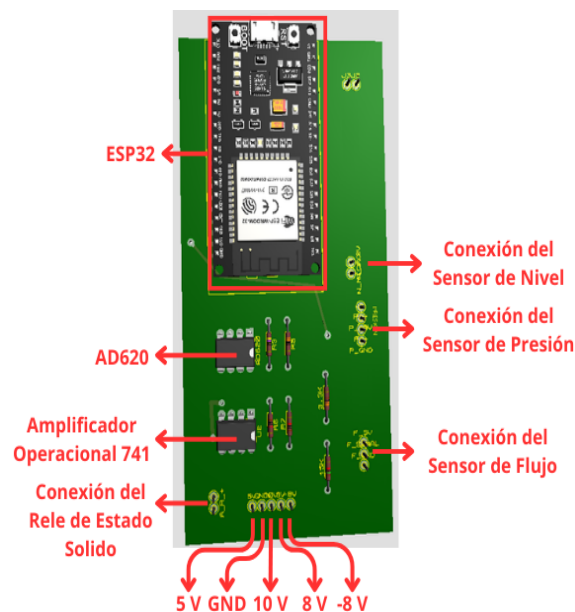


Figure 2. Control board layout

The system's operation begins in the water reservoir, which has a capacity of up to 8 liters. The water volume is regulated by the level sensor, ensuring adequate flow. The water is driven through a $\frac{3}{4}$ " adapter, connected to the inlet of the peripheral pump, and directed to the FS300A flow sensor before entering the Venturi injector through its inlet nozzle.

As it passes through the converging section of the Venturi, the fluid experiences an increase in velocity and a reduction in pressure, generating a suction effect at the central nozzle. This phenomenon creates a vacuum in the pressure vessel, enabling its use in the system. The generated pressure is regulated by solenoid valves, which remain closed when de-energized, ensuring that the vacuum is maintained. Finally, the water returns to the reservoir, completing the operational cycle.

The ESP32 microcontroller is responsible for reading and processing sensor data and for activating the solenoid valves and the peripheral pump. Additionally, owing to its built-in Wi-Fi connectivity, it transmits data in real time to a dedicated web platform.

3D Design

Using Fusion 360 software, a robust structure was designed to house the control circuit and a front panel that ensures the proper positioning of components, such as the vacuum gauge, switches, visual indicators, and safe access to the equipment's internal electronic controls (figure 3).

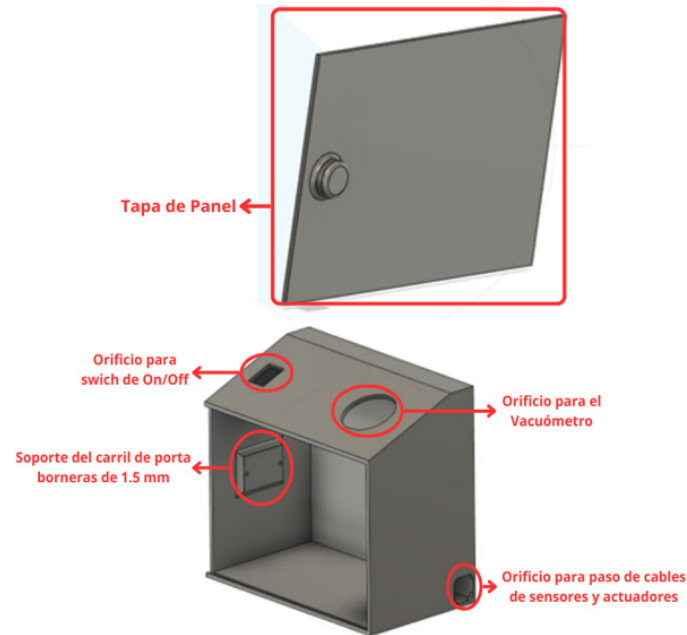


Figure 3. Control Panel Prototype

Integration and Assembly

As shown in figure 4, the system integrates a control panel with the power and control boards. Finally, 1.5 mm terminal blocks were incorporated for an organized distribution of power to the voltage transformer, water pump, and SSR-25 solid-state relay. ESP32 controls the activation of the solenoid valves (220 VAC) and the water pump. The system is turned on and off using a main switch.

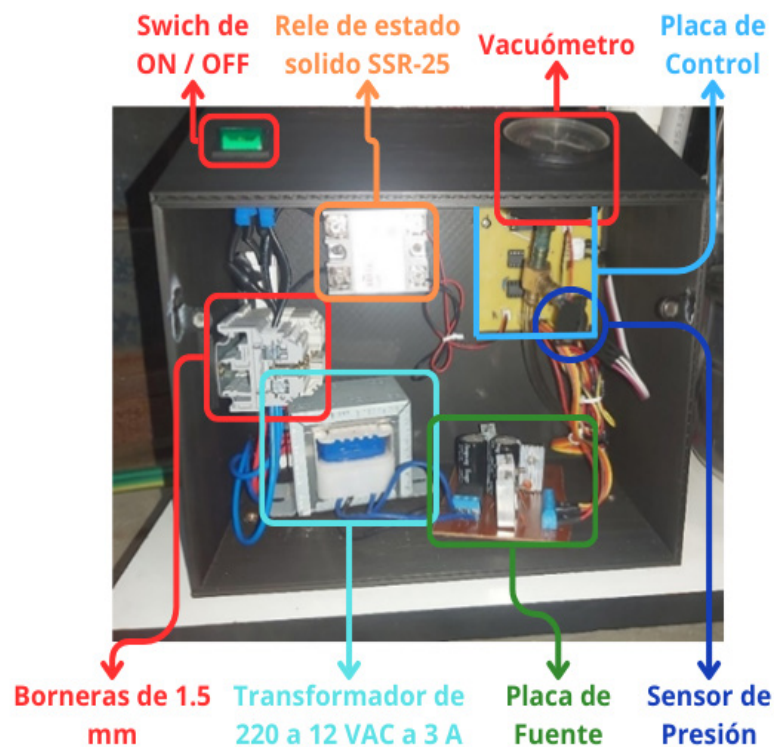


Figure 4. Control Panel Assembly

All the components were integrated into a sturdy melamine base equipped with wheels to facilitate transport and handling of the system (figure 5). The optimized layout of the components, including the water reservoir, pump, pressure vessel, and control panel, resulted in a functional, robust, and efficient prototype that was ready for testing under real operating conditions.

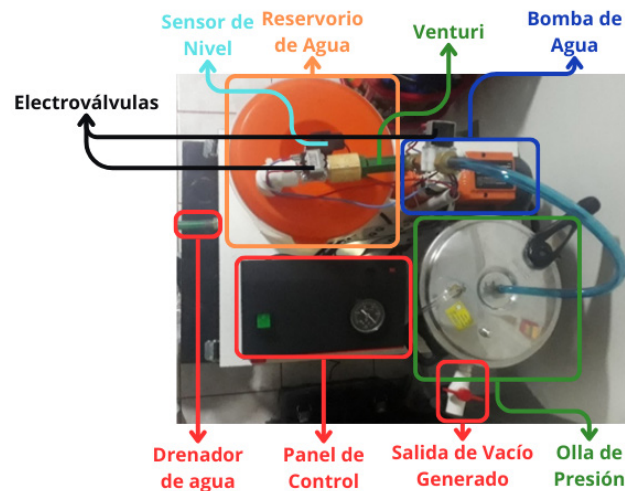


Figure 5. Parts of the Final Control Panel Prototype

Software development

The developed web platform uses technologies such as PHP, HTML, JavaScript, and MySQL for managing and visualizing the data obtained by the system. Its graphical interface was designed to allow real-time monitoring of the measured parameters, as well as remote control of the actuators, including the pump and solenoid valves. Additionally, the database continuously stores sensor readings, facilitating the analysis of historical trends and predictive maintenance of the system.

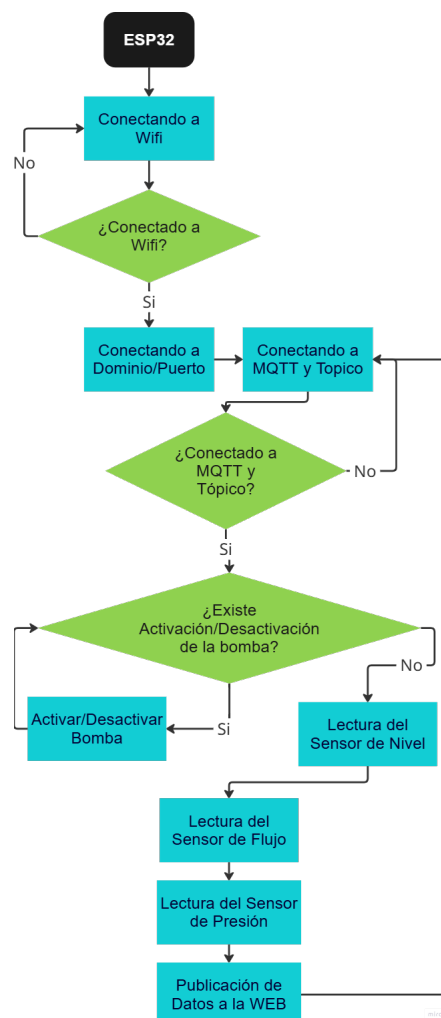


Figure 6. ESP32 Flowchart

Software development focused on ensuring efficient, real-time monitoring of the vacuum system's operation. To this end, an ESP32 microcontroller was implemented, selected for its advanced wireless connectivity capabilities and ability to process multiple

signals simultaneously. Data communication is carried out via the MQTT protocol, enabling efficient transmission of information to a cloud server hosted on AWS.

The ESP32 operational flow follows the sequence shown in figure 6:

- Connection to the Wi-Fi network: Establish communication with the network infrastructure.
- Establishing the connection with the MQTT server: ESP32 subscribes to the corresponding topics to receive commands and send system data.
- Command verification: Monitors for commands to activate or deactivate the pump.
- Data acquisition: The readings from the pressure (MPX2200GP), flow (FS300A), and water level sensors were recorded.
- Data transmission: The captured values are sent in real time to the web server via the MQTT.
- Iterative monitoring and control: The connection to the server and the pump's status are continuously verified, and the cycle is repeated until the required vacuum level is reached.

This control scheme ensures a rapid response to system variations, increasing operational efficiency and facilitating remote monitoring via the web platform.

Calculation of flow and vacuum generated

To perform the system calculations, Bernoulli's equation (4) was applied. The maximum flow rate of the Truper BQAP-1/2-250 pump is 45 L/min (0,00075 m³/s). According to⁽⁶⁾, there is an equivalent table for water density. Typically, in Cochabamba, the temperature varies between 29 and 33 °C, with an atmospheric pressure of 74,140 Pa; therefore, an average value of 1,000 kg/m³ was adopted.

The initial data used in the calculations were as follows:

- Internal inlet diameter: 20 mm
- Internal throat diameter: 8,8 mm
- Truper pump flow rate: 45 L/min = 0,00075 m³/s
- Density of water: 1000 kg/m³
- Atmospheric pressure in Cochabamba: 74,140 Pa

The cross-sectional area of the Venturi inlet is determined as follows:

$$A = \pi \times (d/2)^2 \quad (5)$$

$$A_{\text{entrada}} = \pi \times ((20 \text{ mm})/2)^2 = 314,16 \text{ mm}^2$$

Converting from mm² to m²:

$$314,16 \text{ mm}^2 = 3,1416 \times 10^{-4} \text{ m}^2$$

The cross-sectional area of the Venturi throat is as follows:

$$\text{Area}_{\text{Garganta}} = \pi \times ((8,8 \text{ mm})/2)^2 = 60,82 \text{ mm}^2$$

Converting from mm² to m²:

$$60,82 \text{ mm}^2 = 6,082 \times 10^{-5} \text{ m}^2$$

With these values, the velocities are determined as follows:

$$\text{Velocidad}_{\text{entrada}} = \text{Vazão} / (\text{Area}_{\text{entrada}}) \quad (6)$$

$$\text{Velocidad}_{\text{entrada}} = (0,00075 \text{ m}^3/\text{s}) / (3,1416 \times 10^{-4} \text{ m}^2) \approx 2,387 \text{ m/s}$$

$$\text{Velocidad}_{\text{garganta}} = (0,00075 \text{ m}^3/\text{s}) / (6,082 \times 10^{-5} \text{ m}^2) \approx 12,331 \text{ m/s}$$

Using Bernoulli's equation (4) and considering the density of water ($\rho = 1000 \text{ kg/m}^3$) and atmospheric pressure ($P_{\text{atm}} = 74140 \text{ Pa}$), the pressure at the pore throat can be obtained as follows:

$$P_{\text{garganta}} = P_{\text{entrada}} + (1/2 \times \rho \times (v_{\text{entrada}}^2 - v_{\text{garganta}}^2)) \quad (7)$$

Substituting the values:

$$P_{\text{garganta}} = 74140 \text{ Pa} + (1/2 \times 1000 \text{ kg/m}^3) \times ((2,387 \text{ m/s})^2 - (12,331 \text{ m/s})^2) = 962,104 \text{ Pa}$$

The vacuum generated in kPa is approximately as follows:

$$V_{\text{a'cua Gerado}} = P_{\text{entrada}} - P_{\text{garganta}} \quad (8)$$

$$V_{\text{a'cua Gerado}} = 74140 \text{ Pa} - 962,104 \text{ Pa} = 73177 \text{ Pa}$$

Which is approximately equivalent to:

$$73177 \text{ Pa} \approx 73,177 \text{ kPa}$$

This theoretical value demonstrates Venturi's significant potential for efficiently generating vacuum.

Experiment results

The implemented prototype managed to generate a measured vacuum of approximately 33 kPa. This result is due to practical system constraints, such as pressure drops and limitations in the pump used. Despite these limitations, the system met functional expectations and required clinical parameters, providing real-time data via a web interface accessible to both technical and nontechnical users.

The results obtained from the prototype are graphically represented in Figure 7, clearly demonstrating the system's behavior at 33 kPa. On the web platform, figures representing the flow and pressure sensor readings are displayed, allowing for analysis of the system's performance during experimental tests and comparison with theoretical calculations.

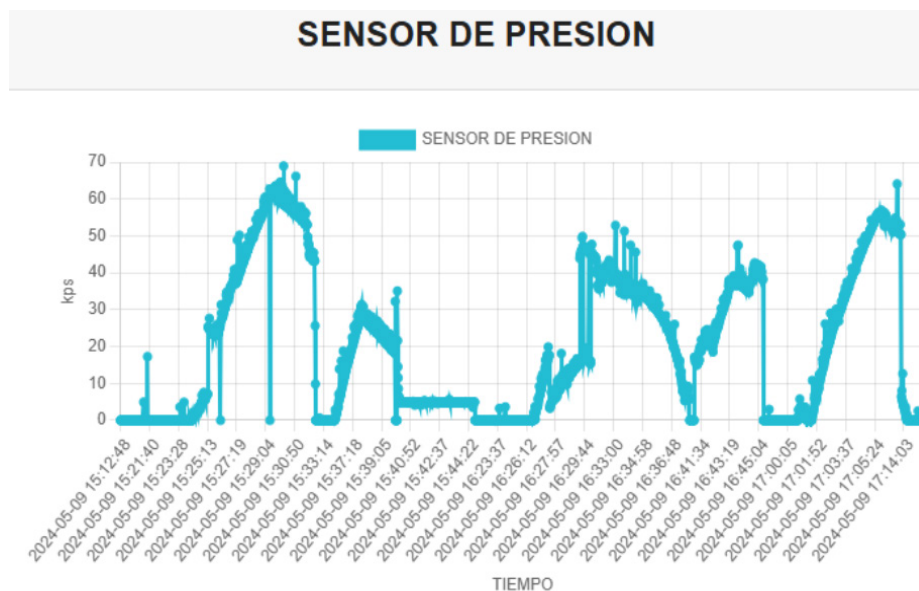


Figure 7. MPX2200GP Pressure Sensor Reading Graph

CONCLUSIONS

Compared with conventional methods of medical vacuum generation, the proposed system proved to be an efficient and economical alternative. The implementation of remote monitoring via sensors and MQTT transmission significantly facilitated the management and supervision of the system. Future studies should focus on optimizing the Venturi design to maximize the vacuum level achieved and validate the system in real clinical environments.

The developed system represents an effective, economical, and viable alternative to conventional systems. However, there are relevant technical considerations that explain why the system does not reach the calculated theoretical value of 73 kPa—only approximately 33 kPa. These practical limitations include friction losses in the tubing, internal turbulence, an actual reduction in the pump's flow rate relative to its nominal specifications, small leaks in the reservoir used (pressure vessel), and differences between the actual and nominal diameters of the Venturi. These considerations are fundamental for future improvements to the prototype.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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AUTHORSHIP CONTRIBUTION

Conceptualization: Brian Arauco Paniagua, Rodrigo Martinez Severich, Eynar Calle Viles, Maria Rene Ledezma Flores.

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Writing – original draft: Brian Arauco Paniagua, Rodrigo Martinez Severich, Eynar Calle Viles, Maria Rene Ledezma Flores.

Writing – proofreading and editing: Brian Arauco Paniagua, Rodrigo Martinez Severich, Eynar Calle Viles, Maria Rene Ledezma Flores.

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