Research Article

Fluid Dynamics Analysis in NDIR Gas Sensor Capsule Designed with Convergent Nozzles

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Abstract

Non-dispersive infrared (NDIR) gas sensor capsules have holes for gas inlet-outlet. The volumetric flow rate of the target gas into the sensor capsule is a significant factor affecting the fast and accurate measurement of gas concentration. The structure and dimensions of the holes in the capsule affect the volumetric flow rate of the target gas. If cylindrical holes are preferred in sensor capsules, it is necessary to enlarge the hole diameter to increase the volumetric flow rate of the gas. However, enlarging the hole diameter in NDIR gas sensors increases IR rays exiting the sensor capsule. This energy loss reduces the light concentration reaching the detector and adversely affects sensor performance. One of the ways to increase the volumetric flow rate of gas passing through the barrier without enlarging the hole diameter is the use of a convergent nozzle structure. Convergent nozzles increase the gas inlet velocity by increasing the pressure difference between the inner and outer points of the barrier, thanks to their structure. In this study, fluid dynamics analysis was conducted in a sensor capsule with cylindrical holes of different diameters 1mm and 1.5 mm, and convergent nozzles of two different sizes 1.5 mm to 1mm and 2 mm to 1 mm. According to the results obtained, when 1.5 mm to 1 mm convergent nozzles are used, the gas's volumetric flow rate is approximately the same as when using cylindrical holes with a diameter of 1.5 mm. Thus, the same result is obtained without increasing the hole area in the capsule by 2.25 times by using convergent nozzles, and additional IR rays are prevented from exiting the sensor capsule. Even higher volumetric flow rate values have been achieved using 2 mm to 1 mm convergent nozzles. With this study, the importance of the structure of the holes where the gas enters the capsule is emphasized for the fast and accurate operation of NDIR gas sensors.

Keywords: Fluid dynamics analysis, NDIR gas sensor, convergent nozzle, volumetric flow rate

1. Introduction

Non-dispersive infrared (NDIR) detection is one of the gas detection methods used in flammable and explosive gas detection systems. NDIR gas detection method, used in detecting hydrocarbon gases, is widely used today because it allows the detection of a specific gas and is a fast and accurate gas analysis technology [1],[2].

The infrared (IR) detection method is based on the absorption of the infrared radiation emitted by the infrared light source at certain intervals by the target gas at specific wavelengths. If there is a target gas in the environment, the gas is sampled into the optical path gap between the infrared light source and the detector by diffusion, inside the NDIR gas sensor capsule. In the detector, the difference in light intensity according to the presence of the target gas is measured. Thus, the target gas concentration is calculated [3].

The flow rate of the target gas into the sensor capsule is one of the essential factors for the sensor to measure accurately and quickly. There are holes on the NDIR gas sensor capsule to allow gas inlet and outlet to the optical path cavity. The amount of gas passing through these holes with a certain surface area per unit of time is written as:

$$Q = \frac{dV}{dt} \tag{1}$$

where Q [L/min] is the volumetric flow rate of gas, V is the volume of hole, and t is the elapsed time [4]. For a cylindrical hole that has a volume $V = A.x$ on the sensor capsule, the volumetric flow rate can be written as:

$$Q = \frac{dV}{dt} = \frac{d}{dt}(Ax) = A\frac{dx}{dt} = Av \tag{2}$$

where A is the hole's surface area, x is the height of the hole and v is the velocity of the gas. Since sampling of the target gas into the sensor capsule occurs by diffusion, some factors affect the volumetric flow rate of the gas. Fick's Law mainly explains the relationship between different factors affecting the volumetric flow rate of gas diffusing through a barrier as follows:

$$\dot{V}_{gas} = \frac{A*(\Delta P)*D}{T} \tag{3}$$

where $\dot{V}_{gas}$ $[ml/dk]$ is volumetric flow rate of the gas diffusing through the barrier, A is the hole's surface area, ΔP is partial pressure difference of the gas across the barrier, D is diffusion constant of gas, and T is the thickness of the barrier. According to Fick's Law, factors affecting the volumetric flow rate of the gas diffusing through the barrier are the surface area, gas concentration, and thickness of the barrier [5].

In fixed gas concentration, increasing the cylindrical holes' surface area is necessary to increase the diffusion ratio on the barrier with a certain thickness. However, some rays scattered from infrared light sources in NDIR gas sensors exit these gas inlet and outlet holes. As seen in the studies in this field, the larger the hole diameter, the greater the number of rays exiting the sensor capsule [5]. This results in a decrease in the light concentration reaching the detector, which is one of the factors affecting the sensor performance [6].

A convergent nozzle with a structure that extends from a larger surface area to a smaller one can be preferred to increase the volumetric flow rate of gas without increasing the gas inlet-outlet hole diameter. The nozzles increase the velocity of the fluid due to the pressure difference caused by their structure [7] according to Bernoulli's equation (4) and continuity equation (5):

$$P_1 - P_2 = \frac{1}{2}\rho(V_2^2 - V_1^2) \tag{4}$$

$$A_1 * V_1 = A_2 * V_2 \tag{5}$$

where P is pressure, ρ is density, V is velocity and A is cross-sectional surface area. As seen in Equation 3, the pressure difference created by the convergent nozzle will increase the volumetric flow rate of the gas diffusing through the barrier without increasing the hole's surface area inside the sensor capsule. This way, the number of IR rays exiting the sensor capsule can also be minimized.

In this study, fluid dynamics analysis was performed in an NDIR gas sensor capsule with a 20 mm diameter designed with cylindrical holes and convergent nozzles, based on Solidworks Flow Simulation [8] software. The analysis was performed with cylindrical holes of 1 mm and 1.5 mm in diameter and convergent nozzles narrowing from 1.5 mm to 1 mm and from 2 mm to 1 mm for different number of holes (3,5,7). The volumetric flow rate of gas was calculated according to the results obtained. Finally, the analysis results were discussed, and suggestions were made for future studies.

2. Methodology

In this study, a sensor capsule placed in a test chamber was designed using Solidworks software. Fluid dynamics analysis was performed using Solidworks Flow Simulation software for the sensor capsule with cylindrical holes of 1 mm and 1.5 mm in diameter and convergent nozzles of 1.5 mm to 1mm and 2 mm to 1mm.

2.1. 3D Modelling

A 3D model of the sensor capsule and test chamber shown in Figure 1 was created to perform the fluid dynamics analysis. The sensor capsule was placed inside the test chamber, where gas was supplied.

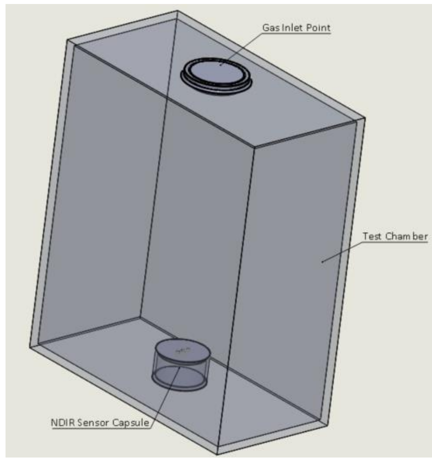

Figure 1: 3D modeling of the system

A 20 mm diameter cylindrical NDIR sensor capsule was designed to be used in the analysis shown in Figure 2. The internal volume of the sensor capsule is 2290.22 mm^3.

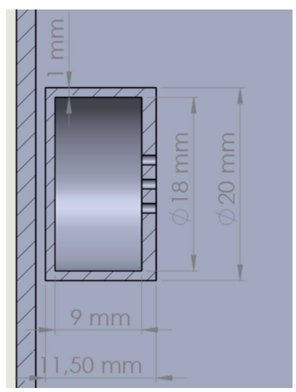

Figure 2: 20mm sensor capsule dimensions

This sensor capsule was placed in a 54x104x124 mm test chamber into which gas flow took place. Figure 3 shows the position of the sensor capsule and distance from the gas inlet point. The gravity direction was set in the same direction as the gas flow direction.

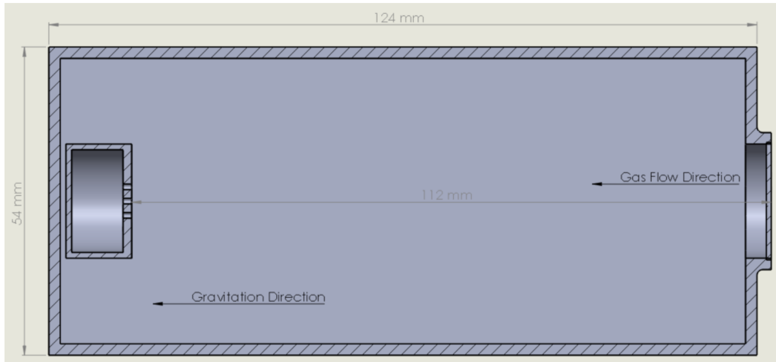

Figure 3: Test chamber dimension

The sensor capsule was primarily designed with cylindrical holes of 1 mm and 1.5 mm in diameter. Next, it was designed with two convergent nozzles, the dimensions of which are also seen in Figure 4(a) and Figure 4(b).

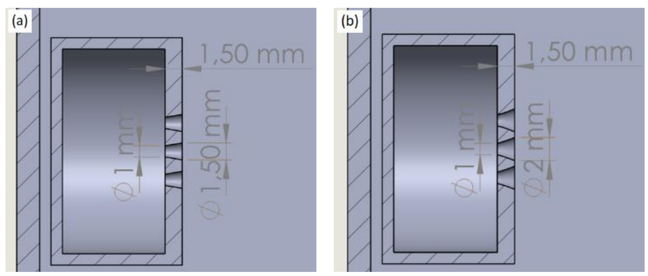

Figure 4: (a) dimensions of 1.5 mm to 1 mm convergent nozzles; (b) dimensions of 2 mm to 1 mm convergent nozzles

For each case, the number of holes was increased as seen in Figure 5, and the distance between the hole's centers is 2.5 mm.

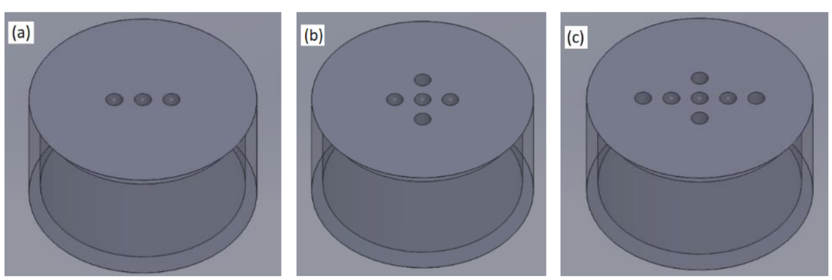

Figure 5: (a) placement of 3 holes on the sensor capsule; (b) placement of 5 holes on the sensor capsule; (c) placement of 7 holes on the sensor capsule

2.2. Fluid Dynamics Analysis

The fluid dynamics analysis made in laminar and turbulent flow types used a mixture of air and methane gas. The volumetric concentration of methane gas in the gas mixture was set to 2.5%. Here, the volumetric flow rate of the gas mixture was set as 0.4

L/min. The characteristics of the ambient conditions (pressure, humidity, temperature) in which the analyzes were made are shown in Table 1.

Table 1: Ambient conditions at fluid dynamics analysis

Temperature	20.05°C
Pressure	1 atm
Gravity	9810 mm/s^2
Humidity	50%
Solid Material	GOLD

3. Results

Firstly, fluid dynamics analysis was performed for 3 holes. All hole types were positioned on the sensor capsule, as seen in Figure 5(a). Analysis was carried out for 1.2 seconds from the moment the methane and air gas mixture reached the sensor capsule. During this time, the pressure change in the holes and the gas inlet velocity were observed in the sensor capsule. The analysis results were recorded at 0.1-second intervals. The analysis was first performed for 3 cylindrical holes with 1 mm and 1.5 mm diameters. Figure 6 shows the pressure and gas inlet velocity cut plot at 0.622 seconds for the sensor capsule with 3 cylindrical holes of 1 mm diameter.

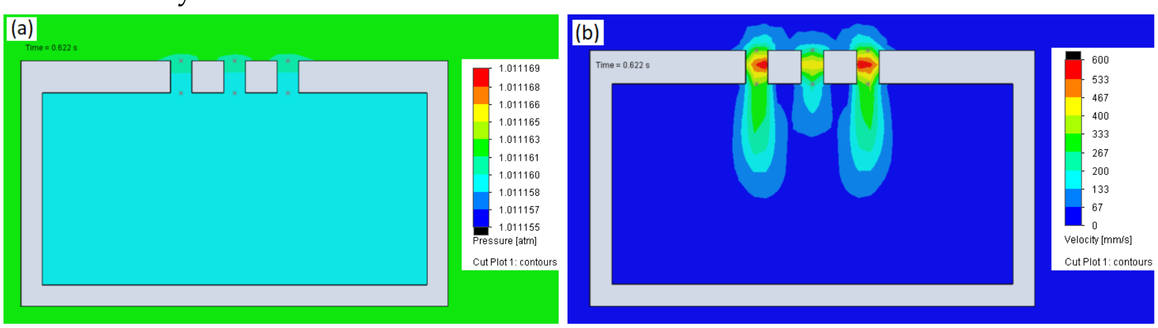

Figure 6: (a) pressure cut plot for sensor capsule design with 3-cylinder holes that 1 mm diameter; (b) gas velocity cut plot for sensor capsule design with 3-cylinder holes that 1 mm diameter

Then, the analysis was repeated by enlarging the diameters of the cylindrical holes to 1.5 mm. The pressure and gas inlet velocity cut plot at 0.622 seconds for the sensor capsule with 3 cylindrical holes of 1.5 mm diameter is seen in Figure 7.

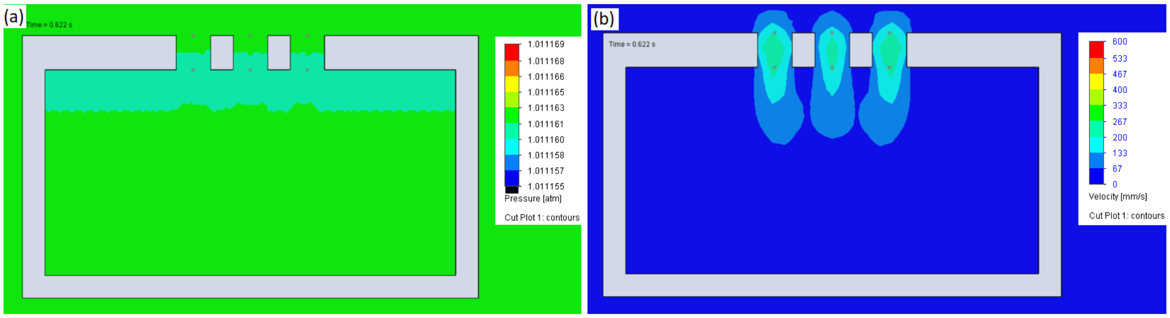

Figure 7: (a) pressure cut plot for sensor capsule design with 3-cylinder holes that 1.5 mm diameter; (b) gas velocity cut plot for sensor capsule design with 3-cylinder holes that 1.5 mm diameter

Secondly, analyzes were performed for the sensor capsule designed with convergent nozzles. Results were obtained for the sensor capsule designed with three 1.5 mm to 1 mm convergent nozzles. Figure 8 shows the pressure and gas inlet velocity cut plot at 0.623 seconds for the sensor capsule with three 1.5 mm to 1 mm convergent nozzles.

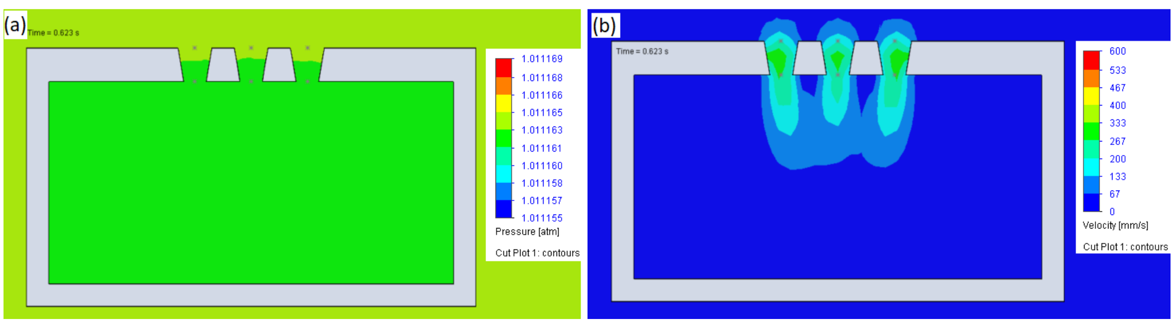

Figure 8: (a) pressure cut plot at for sensor capsule design with three 1.5 mm to 1 mm convergent nozzles; (b) gas velocity cut plot for sensor capsule design with three 1.5 mm to 1 mm convergent nozzles

Then, the analysis was repeated for sensor capsule design with three 2 mm to 1 mm convergent nozzles. The pressure and gas inlet velocity cut plot at 0.622 seconds for the sensor capsule with three 2 mm to 1 mm convergent nozzles are seen in Figure 9.

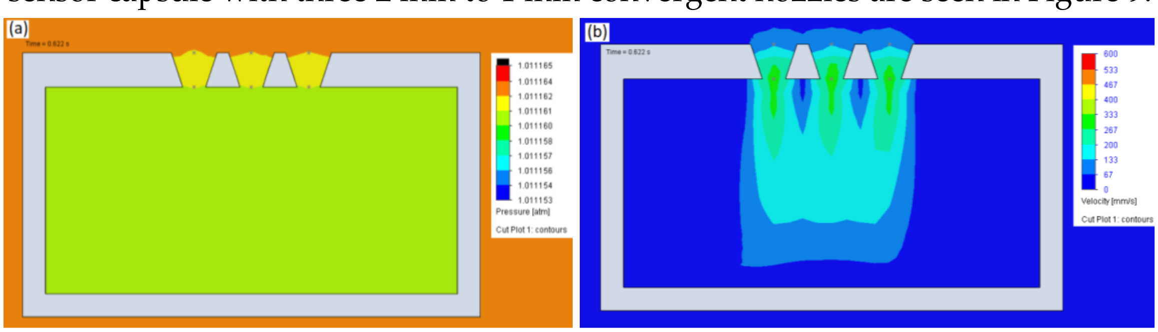

Figure 9: (a) pressure cut plot for sensor capsule design with three 2 mm to 1 mm convergent nozzles; (b) gas velocity cut plot for sensor capsule design with three 2 mm to 1 mm convergent nozzles

Table 2: Total Volumetric Flow Rate for 3 holes

Time(s)	Total Volumetric Flow Rate [mm^3/s] for 3 holes			
	1 mm diameter hole	1.5 mm diameter hole	1.5 mm to 1 mm nozzle	2 mm to 1 mm nozzle
0.1	936.049	1116.396	1081.887	1426.859
0.2	919.671	1093.993	1062.008	1406.753
0.3	920.484	1092.142	1065.969	1363.782
0.4	923.125	1051.287	1065.619	1344.018
0.5	918.461	1020.018	1056.765	1348.382
0.6	911.039	1015.528	1039.545	1352.111
0.7	907.748	1015.071	1022.543	1355.401
0.8	909.399	1015.771	1003.681	1358.367
0.9	909.012	1017.565	1001.513	1360.889
1	911.994	1019.602	993,.658	1363.161
1.1	912.659	1015.290	995.547	1365.283
1.2	913.011	1017.006	994.895	1367.238

According to the gas inlet velocity data recorded at 0.1 s intervals during the 1.2 s analysis period, the total volumetric flow rate data of the gas for each hole type where the number of holes is 3 are shown in Table 2. It is seen that the total volumetric flow rates decreased over time and reached equilibrium around 0.8-0.9 s. The data obtained for cylindrical holes showed that the volumetric flow rate of the gas increased when the hole diameter was increased. However, the results obtained when using 1.5 mm-1 mm convergent nozzles are close to those obtained from cylindrical holes with a 1.5 mm diameter. It is seen that the highest volumetric flow rate data were obtained using the 2 mm-1 mm convergent nozzles.

Table 3: Total Volumetric Flow Rate for 5 holes

Time(s)	Total Volumetric Flow Rate [mm^3/s] for 5 holes			
	1 mm diameter hole	1.5 mm diameter hole	1.5 mm to 1 mm nozzle	2 mm to 1 mm nozzle
0.1	980.889	1199.714	1277.314	1551.669
0.2	974.168	1228.354	1270.211	1572.309
0.3	980.216	1230.635	1220.899	1567.468
0.4	983.650	1205.092	1203.663	1542.961
0.5	980.481	1193.692	1205.232	1481.994
0.6	987.205	1182.869	1209.537	1460.399
0.7	977.218	1178.612	1210.898	1461.424
0.8	975.305	1172.898	1214.623	1463.658
0.9	966.754	1171.779	1215.676	1470.853

1	960.453	1172.213	1219.084	1466.549
1.1	964.175	1172.589	1219.820	1467.743
1.2	955.899	1173.465	1222.929	1467.865

The fluid dynamics analysis was repeated, increasing the number of holes to 5, which were positioned as shown in Figure 5(b). The total volumetric flow rate values of the gas obtained for each hole type as a result of the analysis are shown in Table 3. When the number of holes was increased from 3 to 5, there was an increase in the volumetric flow rate values of the gas obtained in each hole type since the total surface area for the gas inlet-outlet increased.

As shown in the graph in Figure 10, when using 1.5 mm to 1 mm convergent nozzles, the volumetric flow rate values are close to the results obtained for 1.5 mm cylindrical holes. The highest gas volumetric flow rates were obtained at 2 mm to 1 mm convergent nozzles.

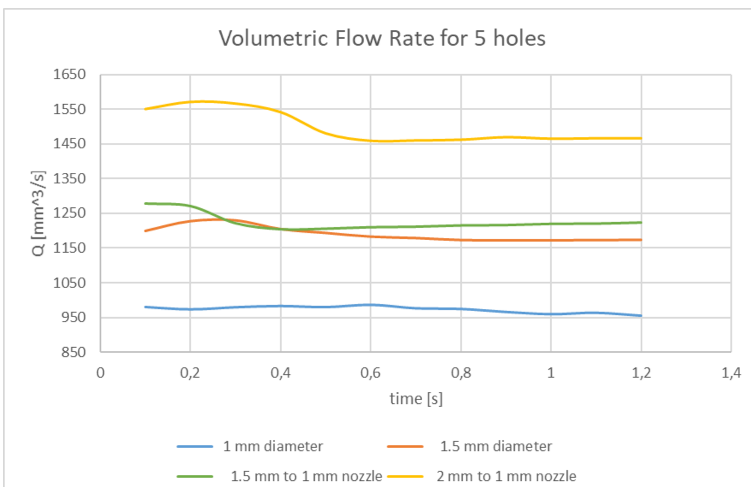

Figure 10: Volumetric flow rate graph by the time for 5 holes

Finally, the fluid dynamics analysis was carried out by increasing the number of holes to 7, whose positions are shown in Figure 5(c). The total volumetric flow rates obtained for the 7 holes are shown in Table 4. As the number of holes increased, volumetric flow rates increased in all hole types because the total surface area increased.

Table 4: Total Volumetric Flow Rate for 7 holes

Time(s)	**Total Volumetric Flow Rate [mm^3/s] for 7 holes**			
	1 mm diameter hole	**1.5 mm diameter hole**	**1.5 mm to 1 mm nozzle**	**2 mm to 1 mm nozzle**
0.1	995.567	1240.106	1285.394	1802.267

0.2	1001.288	1240.993	1268.570	1814.511
0.3	1001.783	1246.245	1256.466	1804.646
0.4	1002.607	1248.095	1219.452	1800.111
0.5	1003.295	1230.554	1217.092	1778.473
0.6	1007.426	1221.983	1217.543	1705.629
0.7	1006.865	1211.852	1217.148	1651.806
0.8	998.858	1212.524	1220.719	1606.429
0.9	998.920	1209.058	1219.624	1575.018
1	987.746	1205.958	1220.521	1564.291
1.1	988.069	1205.840	1219.767	1557.813
1.2	987.763	1205.861	1219.727	1559.451

In all results, the lowest volumetric flow rate values were observed in cylindrical holes with a diameter of 1 mm. The best results were obtained with 2 mm to 1 mm convergent nozzles.

4. Discussion and Conclusion

In this study, fluid dynamics analysis was performed for different gas inlet-outlet hole types in a 20 mm diameter NDIR gas sensor capsule. These analyzes were performed for cylindrical holes with diameters of 1 mm and 1.5 mm and convergent nozzles 1.5 mm to 1 mm and 2 mm to 1 mm. By using a convergent nozzle, it is aimed to increase the volumetric flow rate of the gas without increasing the diameter of the holes opening into the sensor capsule. Because when the hole diameter is increased, the number of IR rays exiting the sensor capsule also increases. This situation negatively affects gas measurement and sensor performance. When all the results were evaluated, the volumetric flow rate of the gas is higher in convergent nozzles compared to a cylindrical hole with a diameter of 1 mm. According to these results, it has been observed that using 1.5 mm to 1 mm convergent nozzles and cylindrical holes with a diameter of 1.5 mm gives close results. Without increasing the surface area of the holes by 2.25 times, the volumetric flow rate of the gas has been increased at about the same ratio thanks to the convergent nozzle structure. It was observed that the gas's volumetric flow rates increased even more when 2 mm to 1 mm convergent nozzles were used. In future work, the convergent nozzle structure can be applied to NDIR gas sensor capsule designs. Convergent nozzle diameters can be optimized according to the barrier thickness of the sensor capsules. Using an appropriate number of convergent nozzles according to the size and volume of the sensor capsules will increase the volumetric flow rate of the gas and prevent the increase of IR beam loss.

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