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Design and Analysis of an Air-Filter Sensor for a Residential Heating and Cooling System

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ABSTRACT

This is a design project of an air-filter sensor to be used in home heating and cooling system. The project includes conceptual design, analysis, implementation, tests and modifications. First, the air quality and power consumption between a clean air filter and a dirty air filter is studied. Then, a photo sensor circuit with an ultra high brightness LED emitter and a phototransistor receiver is used to detect dust particles. A red warning LED lights up when a specified amount of dust is collected on the filter and blocks the light beam between the emitter and the receiver. The emitter and receiver are mounted on a simple fixture and can be easily fitted on any air filter. In addition, the cost analysis shows that this design can significantly reduce the electricity bill if the filters are properly replaced.

INTRODUCTION

A vital part of Engineering Technology (ET) education is the implementation of senior project designs to provide students with the opportunity to apply knowledge gained in other courses to solve practical problems. Engineering Technology students at Old Dominion University usually take such a course in their senior year. Small groups of students (usually two) work on projects identified from one of several sources. The primary source of projects is local industry, usually small businesses. Many of these companies do not have the engineering staff to investigate new products or make major improvement in their manufacturing processes. Contacts with these companies may be initiated by faculty members, the companies themselves, the College's Technology Application Center (an on-campus organization that specializes in promoting economic development for the region through matching industry needs with faculty expertise, student resources and university facilities), or by students who may be working for one of the companies. While student projects may vary substantially, they must contain certain elements: design analysis, computer generated drawings, vendor contacts, literature search for products and manufacturing techniques, material selection and if possible prototype manufacture and testing. The project described in this article was brought to the faculty members through a regional director of the Virginia's Center for Innovative Technology (a sponsoring agency at the Technology Application Center).

DESCRIPTION OF THE PROJECT

When a clean air filter is installed in a heating, ventilation and air conditioning (HVAC) system, people usually forget to replace it because it does not have significant impact on the operation of a HVAC system. However, when the air filter became dirty and remained unchanged, the air quality will deteriorate, and efficiency of the HVAC system will also be reduced [1,2,3]. Since there is no paper or patent discussing this issue, a senior project team is formed to investigate this problem and design an air-filter sensor for a residential HVAC system. There are two teams working on the project. Team 1 performs the design analysis and fabricated the components [4]. Team 2 does air quality tests, cost analysis and testing [5].

Primary objectives of the project are as follows:

1. Measure the air quality difference between a clean and a dirty air filter.

2. Measure the increase in power consumption when using a dirty filter.

3. Design a reliable and low cost sensor, which will be able to send a warning signal when an air filter becomes dirty.

4. Design a simple installation method for the sensor.

5. Perform a cost analysis for the implementation of the device.

AIR QUALITY TEST

The major purpose of installing an air filter in a residential HVAC system is to block the dusty air particles from the incoming air and remove contaminants introduced into the re-circulated air from conditioned space [1]. When a new filter is just installed, it provides little resistance to the airflow. The low resistance provides little friction loss in the system and thus requires less energy for the air mover (motor) than a system with a dirty filter. A clean air filter also produces better air quality and faster response to temperature adjustment during the same operation period of a HVAC system while compared to a dirty/blocked filter. To better analyze the change of the airflow between a clean filter and a dirty filter, a simple apparatus was developed in the ET program [4,5]. This apparatus is a rectangular box that has a fan and motor with openings at the fan discharge and suction ends. The suction end has provisions for the installation of a standard small HVAC filter and a solid sliding gate that covers all or portions of the entrance.

Figure 1 shows the apparatus with a filter and 50% of its area blocked. The centrifugal fan used in this test was driven by a ¾ HP Westinghouse motor. Results of the initial tests were recorded in Table 1, where the average airflow velocity dropped from 820 ft/min with no blockage to 40 ft/min with a blockage of 75% of its total area. The average velocity was measured at the discharge opening that was the same size as the filter. The current drawn by the fan motor was 10.9A with a clean filter versus 9.2A with a 75% blocked filter [5]. Table 3 shows the test results of comparison between a clean and dirty filter in a HVAC system. Within these 11 tests, the average current draw was 11.0A when a clean filter was in place, and 10.5A resulted from a dirty filter. The average airflow velocity was 833 ft/min for a clean filter and 677 ft/min for a dirty filter.

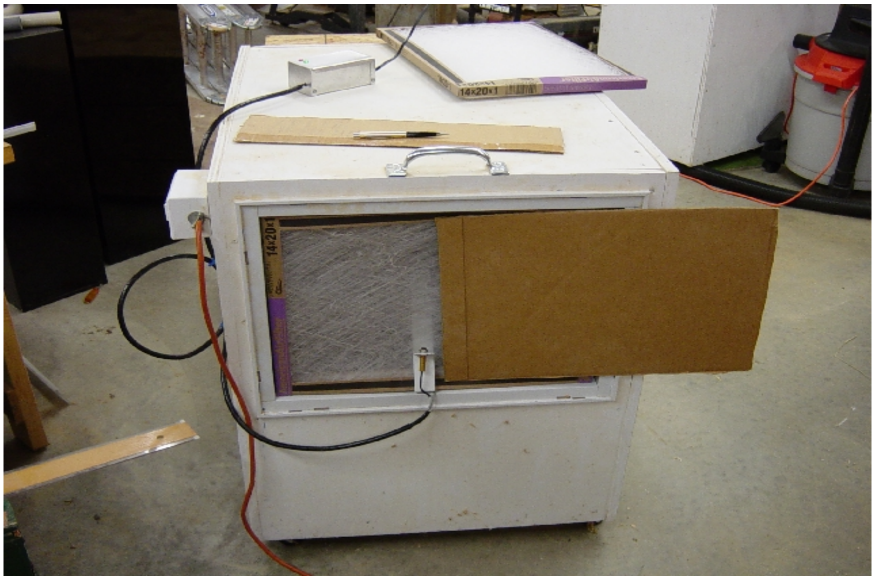

Figure 1. Tests on an Air Filter Blocked by 50% of Its Area

The air quality was measured on a Terra Universal Particle Concentration Meter (PCM) [7], which counts the number of dusty air particles with the diameter of the dusty particle greater than 3 microns within a cubic foot. The results of the experimental measurements are presented in Tables 2 and 4. Table 2 shows that a clean air filter can reduce the number of dusty particles to 77%, while Table 4 shows a dusty filter can only reduce particles to 41.5% [5].

Filter Blockage	**Current Draw (A)**	**Air Velocity (ft/min)**
No blockage	10.9	820
25 percent blocked	10.1	520
50 percent blocked	9.6	470
75 percent blocked	9.2	40

Table 1. Results of Tests from Figure 1

Air Quality Test No.	Initial PCM reading (ppm)	PCM reading 2.5 hrs later (ppm)	Difference	Percent (%) Difference
1	667,800	187,500	480300	71.9
2	1,111,100	226,800	884,300	79.6
3	649,000	135,900	513,100	79.1
4	518,200	77,400	440,800	85.1
5	67,300	36,000	31,300	46.7
6	108,100	45,800	62,300	57.6
7	129,200	31,000	98,200	76
Average	**3,250,700**	**740,400**	**2,510,300**	**77.2**

Table 2. Air Quality Test Results of a Clean Filter

Test No.	Current Draw (A)	Air Velocity (ft/min)
Test 1 with clean filter	10.4	800
Test 1 with dirty filter	10.0	670
Test 2 with clean filter	10.7	830
Test 2 with dirty filter	10.4	690
Test 3 with clean filter	11.0	770
Test 3 with dirty filter	10.5	670
Test 4 with clean filter	10.8	820
Test 4 with dirty filter	10.3	670
Test 5 with clean filter	11.2	850
Test 5 with dirty filter	10.7	680
Test 6 with clean filter	10.9	830
Test 6 with dirty filter	10.6	720
Test 7 with clean filter	11.1	870
Test 7 with dirty filter	10.6	680
Test 8 with clean filter	11.1	830
Test 8 with dirty filter	10.6	660
Test 9 with clean filter	11.4	840
Test 9 with dirty filter	10.2	610
Test 10 with clean filter	11.2	840
Test 10 with dirty filter	10.6	710
Test 11 with clean filter	11.3	870
Test 11 with dirty filter	10.6	690
Average for clean filter	11.009	832.82
Average for dirty filter	10.464	677.273

Table 3. Current Draw and Airflow on a Clean and Dirty Filter

Air Quality Test No.	Initial PCM reading (ppm)	PCM reading 2.5 hrs later (ppm)	Difference	Percent (%) Difference
1	78,500	63,000	15,500	19.7
2	109,500	63,500	46,000	42
3	118,700	73,800	44,900	37.8
4	124,800	71,600	53,200	42.6
5	141,400	81,500	59,900	42.4
6	110,200	61,500	48,700	44.1
7	138,600	65,400	73,200	52.8
Average	**821,700**	**480,300**	**341,400**	**41.5**

Table 4. Air Quality Test Results of a Dirty Filter

POWER CONSUMPTION

The difference in calculation of the power consumption between a clean and a dirty air filter can also be retrieved from the tested data in Table 3. In these tests, the averaged data of a clean and dusty air filter are approximately 832 ft/min in airflow with 11.0A current draw and 677 ft/min in air flow with 10.5A current draw, respectively. It took longer to have the same amount of airflow for the dirty filter than the clean one by a factor of 832/677 or 1.23 that was used in the power consumption calculations. When the fan motor was running in an actual HVAC system, a current draw of 25A was assumed in a HVAC unit. It was also assumed that both systems have the same power factor. Usually, it is less than one and reduces the energy consumption slightly. The following are the power consumption cost calculations in running the systems five hours a day for a 30-day period.

Unblocked Filter Power Consumption Cost Calculations:

P = Power

I = Current

V = voltage

Power Consumption / Sec = P = IV = (11.009 + 25) x 120 = 4321.08 joules /Sec

Power Consumption / Hr = 4321.08 x 3600 sec/hr = 1.55559 x 10^7 Joules/hr

Power Consumption / Month = 1.55559 x 10^7 x 150 hrs = 2.33 x 10^9 Joules = 648 KWH.

Energy Cost = $0.10 per KWH,

Energy Cost /Month = 648 x 0.10 = $64.80

Blocked Filter Power Consumption Cost Calculations:

Power Consumption / Sec = P = IV = (10.464 + 25) x 120 = 4255.68 joules /Sec

Power Consumption / Hr = 4255.68 x 3600 sec/hr = 1.53 x 10^7 Joules/hr

Power Consumption / Month = 1.53 x 10^7 x 1.23 x 150 hrs = 2.83 x 10^9 Joules = 785 KWH.

Energy Cost = $0.10 per KWH,

Energy Cost /Month = 785 x 0.10 = $78.50

The savings for using a clean air filter are about $13.70 per month, which is about 20% of the total HVAC bill in this case.

DESIGN OF THE AIR-FILTER SENSON

The air-filter sensor design is part of the objectives that require the sensor to be reliable and easily fit. One of the designs proposed by students (Team-1) included the installation of a pair of differential pressure sensors mounted on either side of the air filter. When the pressure drop reaches a specified value, a signal will be sent out to activate a warning LED or light. This design, however, needs a significant number of calibrations on the sensing circuit for different types of HVAC systems. It also requires special techniques when installing the sensors on the HVAC system. The sensitivity of this design is another concern.

Home-use air filters are generally translucent, and low-production cost of the sensing circuit is the prime consideration. The faculty recommended a simpler design using photoelectric sensors for this purpose. The design includes a light emitter and a photo receiver. The light emitter emits a beam of light (660 nm), and the receiver detects the amount of light that passes through the filter [6]. If the light beam is partially or fully blocked, the sensor will send a signal to activate the red LED that serves as a warning signal. Two different positions of the sensors are presented in Figure 2, the opposed sensing mode and Figure 3, the retro-reflective sensing mode.

Figure 2. Opposed Sensing Mode

Figure 3. Retro-Reflective Sensing Mode

According to the information from Banner Engineering Corporation [8], opposed mode sensing is the most efficient sensing mode and offers the highest level of sensing energy to overcome atmospheric contamination and sensor misalignment. Retro-reflective sensing mode, however, can be applied when the space on one side is limited. The beam pattern emitted from the emitter can cover a circular area with an approximate five-inch diameter. If an excess gain on the light is used, the beam intensity can increase up to 150 times with an opposing distance of 1 ft. Therefore, the reliability and sensitivity of placing sensors in an opposed direction are higher. This is why the opposed sensing module was chosen in this design where an ultra high brightness LED and a phototransistor were used as a pair of the sensing unit (D4 & Q1) [6]. Two additional transistors (Q 2 & Q3) and associate resistors (R3, R4, & R5) were used to drive red (D3) and green (D2) LEDs for proper indication of the air filter condition. If the filter is clean, the green LED will light. A red light LED was used to indicate a dirty/blocked filter. The supply power to this circuit was regulated through a wall-mount transformer to 5 V power. The detail schematic of this design is presented in Figure 4. As shown in Figure 5, a simple bracket was designed so that it can fit in most of the residential HVAC units. When the light from the emitter is not blocked, a green LED was on as shown in Figure 5. Figure 6 shows that the red LED was on when the filter became dirty. The total cost of this prototype design is under $100.00. This cost can be substantially reduced in a mass-production case.

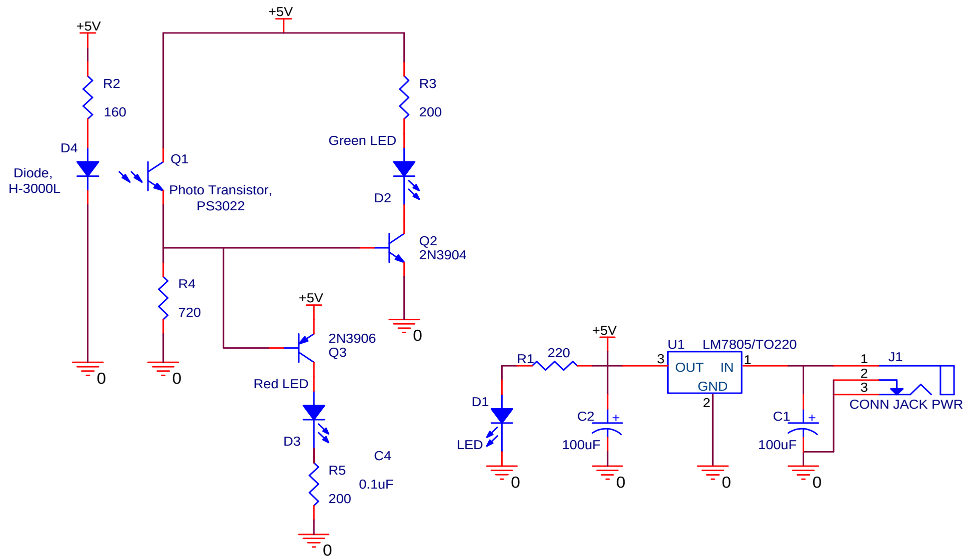

Figure 4. Schematic of the Photo/Light Sensor

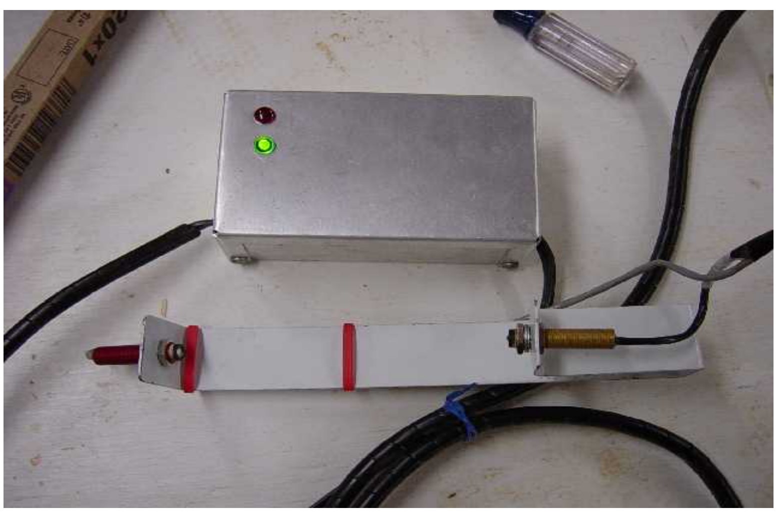

Figure 5. Air-Filter Sensor with Green On When Sensing Light Is Not Blocked

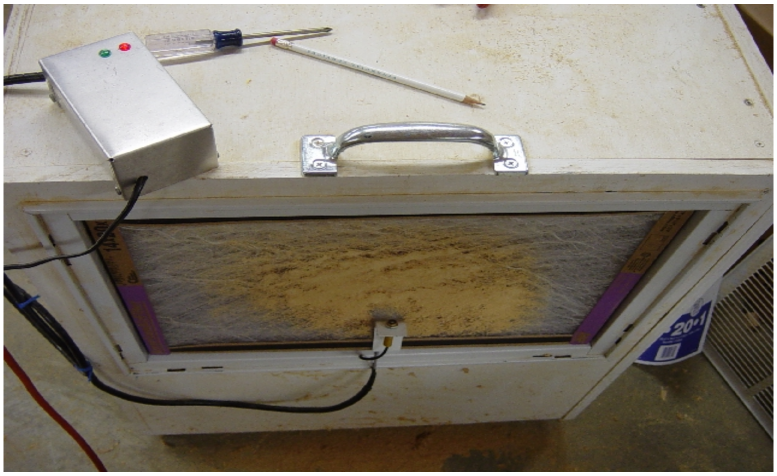

Figure 6. Air-Filter with a Red LED On When Sensing Light Is Blocked

Sensors Power Consumption Cost Calculations:

Power Consumption / Sec = P = IV = 8.17 x 10^{-3} x 120 = 0.98 joules /Sec

Power Consumption / Hr = 0.98 x 3600 sec/hr = 3529 Joules/hr

Power Consumption / Month = 3529 x 720 hrs = 2.54 x 10^{6} Joules = 0.705KWH.

Energy Cost = $0.10 per KWH,

Energy Cost /Month = 0.705 x 0.10 = $0.07

Based on above calculations, the electric bill per month for using the sensor is negligible.

SUMMARY

This project presents an approach for ET students to study and solve the problem of when to replace the air filters of a residential HVAC unit. The sensor was designed and tested. Preliminary tests show that, if a dirty filter is not replaced, then the indoor air quality will aggravate, as the filter loses its function. A dirty filter will also increase the energy bill due to the reduced airflow when compared to a clean air filter. The sensor presented in this paper is very reliable and can be fitted easily to most indoor air filters, which are translucent. The cost of the sensor can be reduced to less than $100.00 in mass production, and the energy consumption of the sensor itself is just a fraction of $0.07/month. The calculated energy savings by using clean filters are approximately $14.00/month. The cost of this sensing unit will be easily justified in less than a year.

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