Energy Harvesting for Powering Distributed and Autonomous Airflow Controllers of a Smart Local Exhaust Ventilation System

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***Abstract*— This paper presents an airflow energy harvester in a local exhaust ventilation (LEV) system based on differential pressure between the inside and outside of the system to power the airflow controller of the system. This helps to realize a distributed system with fewer wiring requirements, which helps to reduce system costs and installation complexity. The energy requirement of the airflow controller was determined and an appropriate turbine design was selected. A prototype was built and tested with an airflow speed of 3.5–16 m/s in a test rig. The energy harvester can generate 0.2 – 20 W of power in the tested conditions, which is sufficient to meet the energy requirement of the LEV system.**

Keywords—airflow controllers, distributed, energy harvesting, local exhaust ventilation systems

I. Introduction

Occupational lung disease is a global issue [1], which is mainly attributed to exposure to occupational hazards such as mineral dust, allergens such as flour and enzymes, and irritants such as cleaning agents [2]. For example, in Great Britain, there are about 12,000 deaths each year and 1.8 million workers suffer from illness due to occupational lung disease [3]. Minimizing exposure to airborne contaminants is the main preventative measure to reduce occupational lung disease [2].

LEV systems are used to capture hazardous vapours, gases, fumes, mists and dust at their source around the workspace [4]. This reduces contaminant dispersion into the surrounding air, improving the health and safety of workers. LEV systems typically comprise an extractor hood, a duct, a cleaning device such as a filter, a fan and a stack. Many systems have multiple hood-duct branches on the same fan/filter/stack [5]. These multi-branch systems are fitted with dampers which are used to carefully balance airflow between branches [6]. Low hood air flows will fail to protect workers whereas high flows may over-extract valuable products and overload filters, causing system failure while also incurring high energy usage and bills [7].

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In practice, LEV systems do not need to run all branches concurrently, depending on the workspace that is being used. The branches can be opened or closed using dampers. As branches are opened and closed, fan speed adjusts to maintain a constant pressure, giving roughly the right flow in the open branches. Fan energy consumption follows a cube law with airflow and a square law with pressure [8]. Thus, a small reduction in either parameter can deliver much larger savings in energy consumption and also electricity bills. R&B Industrial introduced the SmartAIR® LEV system using modulating dampers and venturi-type flow metering on every branch to precisely control flows through all branches and minimise fan pressure, achieving significant energy and cost savings [9].

Many industries do not have appropriate control measures such as installing LEV systems in the past. This is due to a lack of knowledge in this area given that the Control of Substances Hazardous to Health (COSHH) Regulations in the UK only became freely available in 2002 [10]. Many LEV systems need to be retrofitted in existing plants but come at high installation costs [11], especially with cabling-related costs [12]. There is a potential to eliminate cabling requirements between branches and a central controller. The cables for system communication can be replaced by wireless technologies [13].

Energy harvesting has shown potential as an alternative power supply to mains power or battery [14]. However, many energy-harvesting research in air ducts only focuses on powering wireless sensors with harvested power in the range of microwatts to milliwatts [15], [16]. Thus, this work presents an

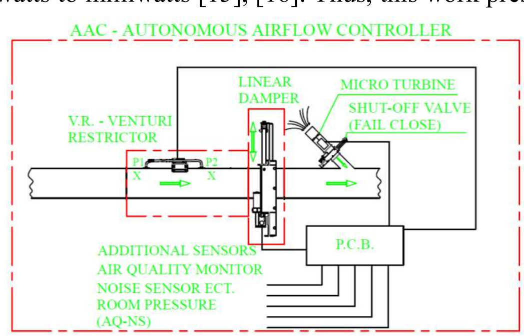

Fig. 1. Illustration of the AAC.

airflow energy harvester with watt levels of power for realizing an autonomous airflow controller (AAC) at each branch of the SmartAIR® LEV system. This helps to reduce cabling costs and enable industrial automation with edge computing capability at individual branches of an LEV system.

II. System Description

The AAC comprises a pair of differential pressure sensors to measure air velocity through a venturi restrictor [17], a linear damper to modulate the opening of an air duct, an airflow energy harvester as the main power supply of the AAC, and a printed circuit board (PCB) that contains a microcontroller as the main controller and interface to additional sensors, a wireless module to communicate with the central controller or other AACs, and a power management circuit to condition the harvested energy for powering the AAC and also recharging an energy storage device, as illustrated in Fig. 1.

Airflow energy harvesting is the natural choice since airflow is always present in the ducts of LEV systems. The airflow within the header duct created a pressure difference that forces air through the turbine duct. A turbine is used to convert the airflow into electricity. The turbine is installed in a turbine duct to minimise interference on the air stream in the header duct and accumulation of contaminants on the rotor, which degrades performance [18]. The turbine duct is located behind the linear damper so that energy harvesting is still possible even when the damper is fully shut. In between the turbine duct and the header duct is a shut-off valve to close the turbine duct when energy harvesting is not needed.

The power P that is available from the airflow in the header duct and generated by the energy harvester P_{gen} are given by (1) and (2) [19], respectively.

$$P = \frac{1}{2}\rho v^3 A \tag{1}$$

$$P_{\text{gen}} = \eta C_{\text{P}}\, pvA \tag{2}$$

where ρ is the air density, v is the air velocity, A is the area of the duct, η is the mechanical to electrical efficiency, C_{P} is the power coefficient of the turbine, which has a maximum value of 59.3% according to Betz's law and p is the pressure, which arises from $\frac{1}{2}\rho v^2$.

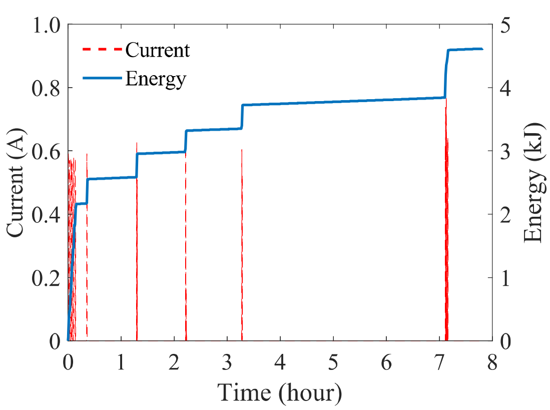

Fig. 2 Current and energy required by the SmartAIR® LEV system's damper.

III. Implementation and Test

The energy consumption of the AAC is determined first so that a suitable turbine can be developed and built using commercially available components. A test rig is then built to evaluate the capability of the energy harvester to meet the energy requirement of the AAC.

A. Energy Requirement

The nominal power consumption of the AAC would be the minimum power that the energy harvester must harvest when the LEV system is in use. The electronics, which mainly comprise the microcontroller, wireless module, and sensor that form a wireless sensor node are estimated to consume a total power of 66 µW–66 mW depending on the operation [20]. The linear damper consumes energy whenever it changes position to vary the flow rate. Although the energy consumed varies on a case-by-case basis, the current consumption of a 24 V damper in an operational LEV system at Tucker Joinery, Andover, UK was measured for almost 8 hours, which is a typical business hour to have a better estimation. Fig. 2 shows the measured current drawn by the damper and the calculated energy usage of about 4.6 kJ during that duration. Assuming the electronics consume 66 mW during operational time and 66 µW for the remaining time outside of business hours, the total energy required by the AAC is estimated to be no less than 7 kJ per day. Considering the efficiency of the energy harvesting power management circuit at around 75% [14], the total energy that the harvester needs to generate is about 9.3 kJ.

B. Airflow Energy Harvester

The energy harvester needs to produce a minimum electrical power of 325 mW if it is operating all the time whenever a LEV system is operating. If the energy harvester is to operate for one hour or less, it needs to produce at least 2.6 W. A peak power output of 20 W is required for the energy harvester to instantly meet the power demand of the damper. A 40 W brushless DC motor (Maxon, ECXTQ22XL KL A STD 48V) was chosen as the generator to satisfy the power demand and for its longer life span than brushed motors.

The number of rotor blades is associated with the tip speed ratio λ, as given by (3) [19], where ω is the rotational speed of the rotor in radians/second, R is the rotor radius, and v is the airflow speed. The diameter of the header duct varies from 100 to 500 mm. As the turbine duct cannot be larger than the header duct, the rotor diameter is limited to 97 mm. The rotational speed of the rotor should be as high as possible to turn the shaft of the generator for it to output high power. The chosen generator has a speed constant of 228 rpm/V. Thus, ω should be more than 2000 to produce sufficiently high voltage for circuit operation. The airflow speed in the air duct of LEV systems could be in the range of 4–12 m/s [21]. The resultant λ is around 2.5–3, which

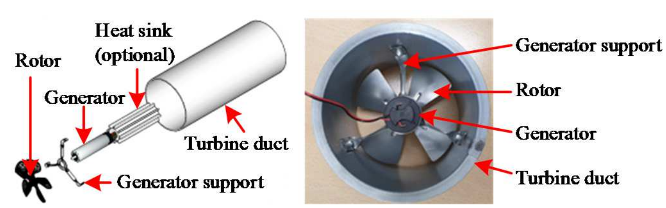

Fig. 3 Illustration of the exploded view and image of the energy harvester.

corresponds to an optimal blade number of 3–8 [19]. A four-blade rotor (FB-96-4-30-ACW-B-1) is used in this work. The energy harvester built is shown in Fig. 3.

$$\lambda = \frac{\omega R}{v} \tag{3}$$

C. Test

A test rig as shown in Fig. 4 was built at R&B Industrial to test the energy harvester. The test rig has a 2.2 kW three-phase inverter-controlled fan to generate different airflow speeds of 3–16 m/s, which were measured using differential pressure sensors in the fully opened ⌀ 200 mm header duct. The energy harvester was connected to a rectifier made of four Schottky diodes (PMEG10030ELP). The rectified output was connected to a DC electronic load (Tenma 72-13210), which was manually tuned to determine the maximum output power.

The effect of different header duct openings on the harvested energy due to the position of the linear damper was determined too. The position was varied at 100% (fully opened), 75%, 50%, 25%, and 0% (fully closed) as shown in Fig. 5 while the exhaust fan was set to run at a constant power in all the tests.

IV. Results and Discussion

Fig. 6 shows the output power and voltage of the energy harvester after rectification at different airflow speeds in the feed duct. The power increases exponentially from 0.21–20.6 W as the airflow speed increases from 3.5–15.7 m/s. At an airflow speed of 5 m/s, the power generated meets the minimum energy requirement of the AAC at 0.43 W for 8 hours of operation, when the efficiency of the power management circuit is considered. The power output at 8.8 m/s is 3.47 W, which meets the energy requirement of the AAC for a day in one hour after power conditioning.

Even at a low airflow speed of 3.5 m/s, the output voltage from the generator is 5 V, which is sufficiently high for the electronics to operate. This ensures the energy harvesting system can start autonomously without any complex step-up circuit and backup energy storage. At the airflow speed of 15.4 m/s, the voltage is around 36.8 V, which is a fairly common range of voltage for power electronics. Therefore, many standard power management circuits may be used to condition the energy from the airflow energy harvester without having to use a customized design which may increase the system cost drastically.

Fig. 7 shows the total energy generated by the energy harvester and the energy that can be used considering a circuit efficiency of 75% in 12 hours. The energy generated ranges between 9–889 kJ where about 6.8–667 kJ of energy is usable by the AAC after the power management circuit. Using 9.33 kJ as an example, sufficient energy can be accumulated in about 8 minutes when the airflow speed is 15.7 m/s. Even at the low airflow speed of 3.5 m/s, it is still possible to accumulate enough energy for the day in about 12 hours. With the airflow speed slightly increased to 5 m/s, about 18 kJ of energy can be generated by the energy harvester in 12 hours. In reality, the

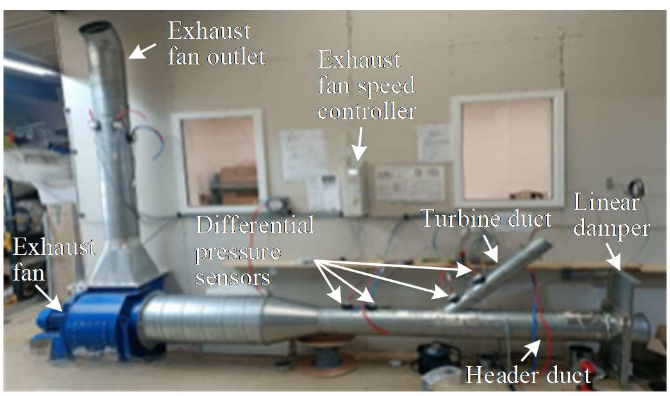

Fig. 4 Image of the test rig.

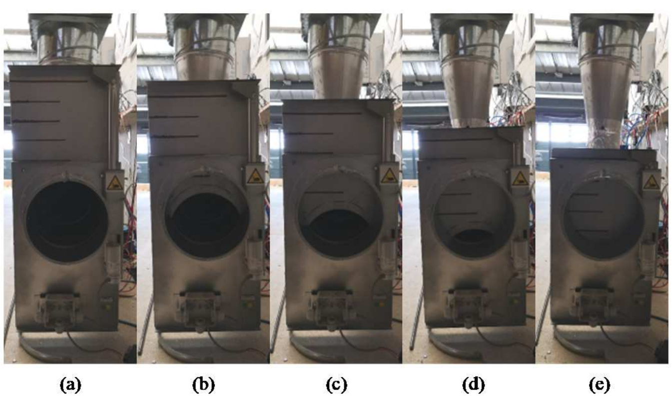

Fig. 5 Different positions of the linear damper at (a) 100%, (b) 75%, (c) 50%, (d) 25%, and (e) 0%.

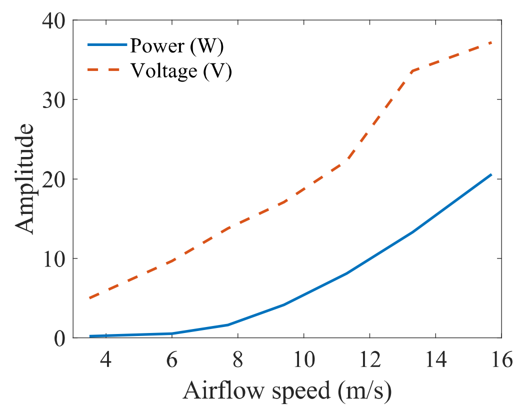

Fig. 6 Power and voltage generated at different airflow speeds.

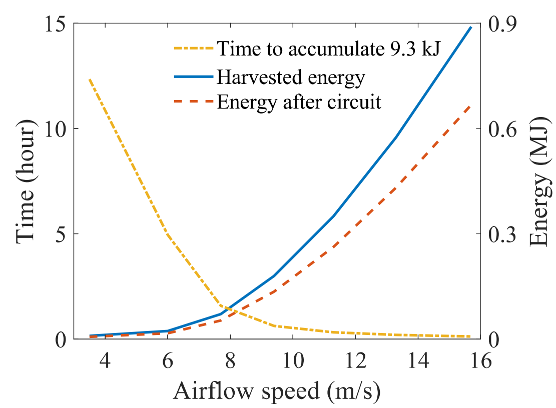

Fig. 7 Energy accumulated in 12 hours and the corresponding charging time to provide 9.3 kJ at different airflow speeds.

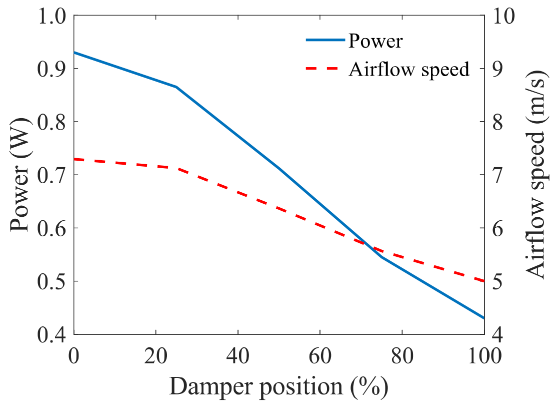

Fig. 8 Power generated by the energy harvester and the corresponding airflow speeds with different positions of the linear damper.

airflow speed is unlikely to stay very low all the time. Thus, the energy harvester is envisaged to be able to generate sufficient energy for the AAC within 8 hours. With the energy in the tens to hundreds of kilojoules range, there is enough energy to use high-performance microcontrollers for edge computing in the AAC or power some nearby external sensors and actuators.

Fig. 8 shows that as the linear damper alters its position which subsequently changes the opening of the header duct, the energy harvester produces different power levels due to the changes in airflow in the duct. When the linear damper is fully opened, the airflow speed in the turbine duct is the lowest at 5 m/s and hence has the lowest power at 0.43 W. As the position of the linear damper is lowered to 75%, the airflow increases slightly, which causes the power to increase to 0.55 W. Further lowering of the damper position sees a similar trend where the airflow speed increases and causes the power generated to increase. The power reaches 0.93 W when the linear damper is fully shut, which is more than double the power when the linear damper is fully opened. It should be noted that in the event of a fan stall, some stall recovery techniques include bleeding in the air to change the airflow velocity via changing the position of the damper. The energy harvester would recover some of the energy from this process [22].

V. Conclusion

Various parts of industrial equipment are usually hard-wired. This work presents a way to realise a LEV system with distributed AAC using energy harvesting. This could transform future industrial equipment to be more modular and flexible as some parts are autonomous in terms of energy and computing capabilities. Cabling requirements of systems are reduced with the introduction of energy harvesting, which saves costs from less material and shorter labour installation time. The energy harvesting system was designed and installed in a way that the energy harvester does not sit in the main header duct of the LEV system where it could be easily contaminated and interfere with the LEV system operation. The energy harvester can work over a wide range of airflow speeds from a low speed of 3.5 m/s to high speeds of over 15 m/s. The power generated ranges from 0.21–20.6 W when the energy harvester is subjected to the airflow speed of 3.5–15.7 m/s. The high output power capability of the energy harvester ensures the energy requirement of the AAC can be met, with the potential to introduce more functions such as condition monitoring and edge computing for self-diagnostics with the energy surplus, realizing a smart connected industry.

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