A NOVEL METHOD TO DERTERMINE AIR LEAKAGE IN HEAT PUMP CLOTHES DRYERS

Pradeep Bansal*, Amar Mohabir and William Miller
Building Equipment Group, Energy & Transportation Science Division
Oak Ridge National Laboratory
One Bethel Valley Road, MS-6070, Oak Ridge, TN 37831, USA

*Email: bansalpk@ornl.gov; Phone: +1-865-576-7376; Fax: +1-865-574-9338

ABSTRACT

A heat pump clothes dryer has the potential to save up to 60% energy as compared with the conventional vented electric dryers, Pescatore and Carbone 2005.. Although heat pump clothes dryers (HPCD) offer higher energy efficiency; it has been observed that they are prone to air leakages, which inhibits the HPCD's gain in efficiency. This study serves to develop a novel method of quantifying leakage, and to determine specific leakage locations in the dryer drum and air circulation system. The basis of this method is the American Society of Testing and Materials (ASTM) standard E779 – 10, which documents a procedure to determine the air leakage area in a household ventilation system through fan pressurization. This ASTM method was adapted to the dryer system, and used to compute the leakage areas in the dryer. Easily accessible leakage points were quantified: the front and back crease (in the dryer drum), the leakage in the duct, the air filter, and the remaining leakage in the drum. The procedure allows investigators to determine major components contributing to leakage in HPCDs, thus leading to component design improvements that result in more efficient HPCD systems.

Key words: Heat pump clothes dryer, HPCD, efficiency, air leakage, vented dryer.

Nomenclature

Q: Leakage volumetric flow rate, $\left[\frac{m^3}{s}\right]$
C: Air leakage coefficient, $\left[\frac{m^3}{s*Pa^n}\right]$
n: Pressure exponent
ΔP: Pressure gradient from drum to ambient, $[Pa]$
K: Orifice outlet to inlet cross sectional area ratio
A_o: Outlet orifice cross sectional area, $[m^2]$
ρ: Air density at the leakage point (70°C, 70% relative humidity), $\left[\frac{kg}{m^3}\right]$
ELA: Effective leakage area, $[m^2]$
P^*: Test pressure, $[Pa]$

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1. INTRODUCTION

Heating of air is an expensive process and is the primary energy cost in all types of residential dryers. The majority of clothes dryers (about 80%) in U. S. households are vented electric dryers, where air flows in an open cycle, first being heated by an electric heater, then entering the clothes drum and finally exhausted to the ambient air. The exhaust results in about 40% loss.Myers, Franco and Lekov (2010) concluded that vented electric dryers were less efficient than a HPCD primarily due to the lost heat vented by electric dryers. In addition, the vented clothes dryer needs extra ducting to exhaust the moist air outdoors. However, in a heat pump clothes dryer (HPCD), shown in Figure 1, the air is circulated in a closed loop, eliminating the need of an exhaust duct. Hence most of the heat is retained inside the HPCD.

The refrigeration cycle of a HPCD consists of four main refrigeration components- an evaporator, a compressor, a condenser and an expansion valve. The cycle operates in a closed loop where conditioned and heated air from the condenser enters the drum, gains moisture from the wet clothes and returns through an air duct to the inlet of the evaporator. The air duct also houses the condenser.(Figure 1). The moist air is dehumidified as it flows over the evaporator. Condensate drains off the evaporator and collects in a pan. A pump drains the pan at five-minute intervals to a house drain. The dehumidified air flows over the condenser where it is sensibly heated prior to reentering the dryer drum.

Although heat pump clothes dryers offer higher energy efficiency through air recirculation, it is likely that various components are prone to air leakage (of up to 40%), resulting in loss of efficiency. One way of improving the energy efficiency of a HPCD, is to make the air circulation system as leak-free as possible. Leakage points may be created through manufacturing defects or damaged components and are expected to be scattered in parts of both

the drum and air circulation duct of the HPCD. Although clothes dryers have been studied extensively [1-15] in the open literature, studies and data on the leakage aspect is sparce. This study serves to develop a method of quantifying leakage from HPCDs, and to determine specific leakage locations in the dryer drum and air circulation system.

2. AIR LEAKAGE TESTING

Figure 1 displays a schematic of the HPCD showing its components and various leakage points. There are two general areas of leakage, the dryer drum and the air circulation duct. The components of the dryer drum that contribute greatest to its leakage are the front rotation crease, and the back rotation crease. The air circulation duct is not accessible; however the components that contribute to its leakage are the front grill, back grill, and air filter. The front and back grill of the dryer connect the air flow from the air circulation duct to the dryer drum.

The basis of this the proposed clothes dryer air leakage test method is the American Society of Testing and Materials (ASTM) standard E779 – 10, which is used to determine air leakage area in a household ventilation system through fan pressurization [1]. This ASTM method is adapted to the clothes dryer system, and the leakage area is determined by an analysis of the leakage volumetric flow and pressure relationship. A Minneapolis Duct Blaster is used to pressurize the dryer drum and an accompanying pressure and flow gauge (Model DG – 700) is used to measure the Duct Blaster air flow rate and drum pressure drop. Successful verification and implementation of this method allows determination and quantification of leakage points in the dryer system, further providing grounds for extension to other air leakage scenarios.

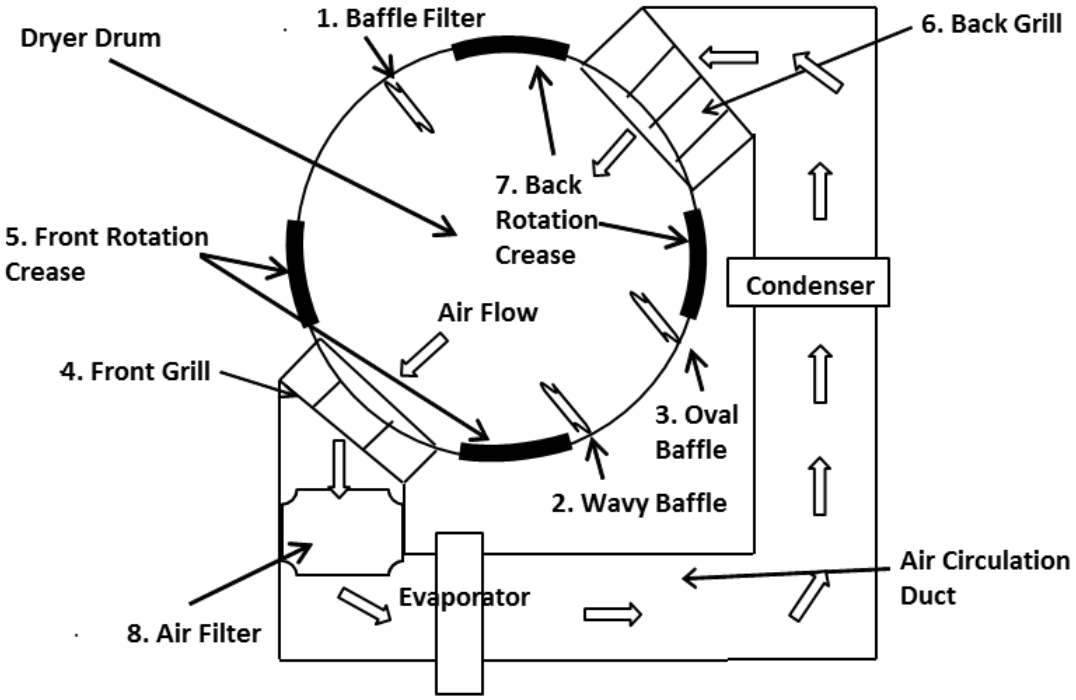

Figure 1: Schematic of heat pump clothes dryer (HPCD) and locations for air leakage

3. THEORY

ASTM Standard E779-10 uses the following correlation to relate the leakage volumetric flow rate and driving pressure:

$$Q = C(\Delta P)^n \tag{1}$$

where

Q is the volumetric flow of air passing through an effective leak area of the building,

ΔP represents the pressure drop across the building, and

C and n are determined through a regression analysis of the Q and ΔP data.

Since leakage points are hypothesized to occur through manufacturing defects, they are physically small in cross sectional area, and are assumed small orifices using the following relationship between leakage volumetric flow rate and drum pressure drop:

$$Q = KA_o\sqrt{\frac{2\Delta P}{\rho}} \tag{2}$$

Equation (2) is the orifice equation derived from Bernoulli's principle of flow along a streamline. Combining Equations (1) and (2) yields a relationship for calculating the effective leak area (ELA),Equation (3)

$$A_o = ELA = \frac{C\Delta P^{\left(n-\frac{1}{2}\right)}\left(\frac{\rho}{2}\right)^{\frac{1}{2}}}{K} \tag{3}$$

Note that the ASTM standard assumes that all orifice lengths are negligible, thus the value of K is 1. Furthermore, adapting Equation (3) to the dryer system requires the following assumptions:

- The dryer drum and air circulation system leaks are similar to those of a household ventilation system.
- During steady state operation, the leakage volumetric flow rate equals the inlet fan flow rate as a consequence of conservation of mass.
- The driving force for leakage is the pressure difference between the drum pressure and the ambient pressure.

A major difference between a dryer air circulation system and a household ventilation system is size – the dryer circulation system is much smaller. In both cases, the points at which air leakage occurs are small defects which are approximated as orifices. The phenomenon of leakage in both cases is therefore identical, justifying the use of Equation (1) and (2) in the dryer system. During steady state operation, the only points of air flow in the system are the inlet fan pressurization, and the outlet leakage. Thus by conservation of mass, the volumetric flow rate at the fan inlet must be equal to the combined leakage volumetric flow rate of all leakage points of

the HPCD. The drum and air circulation system pressure is uniform once pressurized by the fan at a constant flow rate, and the only other pressure region is the ambient pressure. Therefore this pressure gradient provides the driving force for the leakage volumetric flow rate.

The DG - 700 gauge used to measure the volumetric flow rate and drum pressure drop also determines the effective leakage area at a reference pressure (P*) of 50 Pa based on the following empirical correlation given in the DG - 700 manual [2]:

$$ELA = \frac{Q\left(\frac{50}{P^*}\right)^{0.65}}{7.495} \tag{4}$$

The most accurate results are obtained with the duct blaster and DG-700 when the test pressure, P^*, is 50 Pa. The value of Q is obtained from the same ASTM correlation in Equation (1), and the values of C and n are fixed to 6.26 and 0.5 respectively, as specified in the Duct Blaster manual [3], for ring 3 providing a flow diameter of xx.x m. The DG - 700 device assumes a K value of 0.61 (for building operations), which was corrected to a K value of 1 for application to the HPCD. A comparison will be made from the effective leakage area using Equations (3) and (4).

4. METHODS

The experimental set up primarily consisted of three main components, namely a Minneapolis Duct Blaster fan, a flexible extension duct, and the HPCD. All of these components were connected in series as shown in Figure 2. Figure 3 shows a photograph of the actual layout of the leakage measurement apparatus and the HPCD prototype. The flexible extension duct is an airtight aluminum duct connecting the duct blaster fan to the dryer drum by attachment through a metal fitting bolted onto the drum door. The accompanying DG - 700 gauge, also provided by

the manufacturer of the duct blaster, computes the fan volumetric flow rate and drum pressure drop. The duct blaster incorporates a variable speed fan [3], which has three inlet rings of varying inner diameter. The rings attach to the fan to provide a range of volumetric flow rates and related pressure drops. The ring of the smallest diameter (ring 3) was most suitable for our application since it provided pressure drops that were in the fan's calibration region, and closest to the operating pressure of the HPCD.

The static air pressure was measured at the inlet of the fan housing and in the dryer drum. A pressure transducer accurately measures the pressure drop responsible for the fan volumetric flow rate.A static pressure tap was installed inside the drum for internal drum pressure. The DG - 700 gauge has two independent pressure channels, which were connected to both pressure measurement points. Both of these channels were referenced to ambient pressure, i.e., the pressure drop of the fan is the fan pressure referenced to the ambient pressure. The fan volumetric flow rate was controlled by a variable speed fan controller.

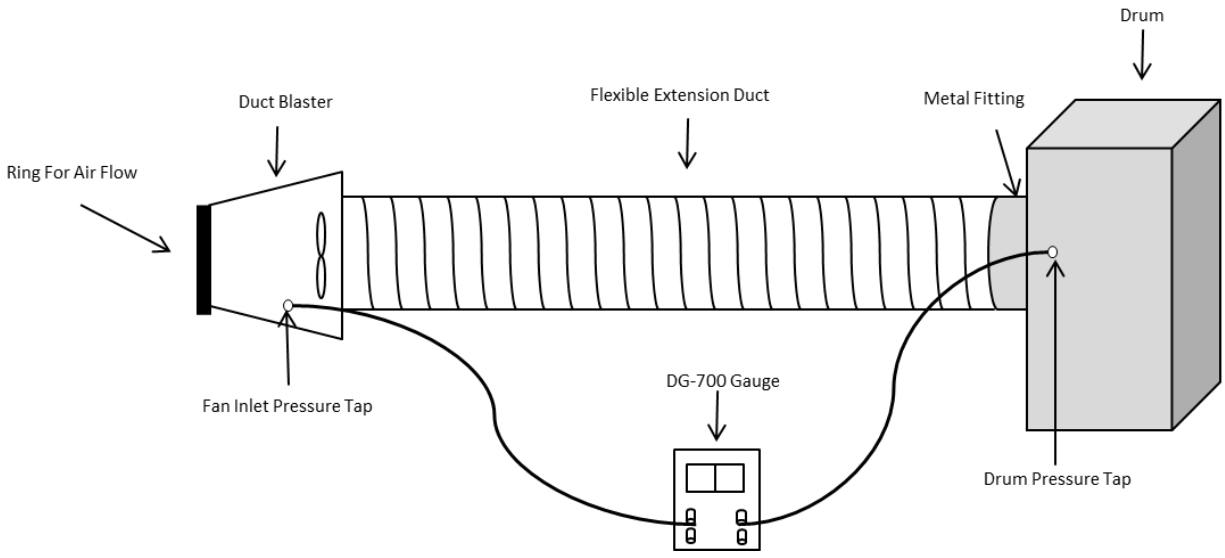

Figure 2: Schematic of experimental setup

Figure 3: Layout of the air leakage test apparatus for the HPCD prototype

The independent variable measured by the leakage test apparatus is the pressure drop between the drum and the ambient. Accordingly, the fan was controlled to pressurize the drum from 30 to 120 Pa for all sealed configurations, where seven pressure drop and leakage volumetric flow rate data pairs were recorded within that range (the duct blaster manufacturer recommends a minimum of six data points for accurate curves). These data points were subsequently plotted and a power regression was formulated for each sealed configuration to calculate a leakage area.

The approach used to determine the leakage from various points within the HPCD began with fully sealing all the components. This provided the baseline leakage or miscellaneous losses. Following this, each component was unsealed individually to determine its contribution to leakage. During initial testing, it was determined that the baffles did not contribute significantly to leakage, therefore they were not considered in the air leakage analysis. The components which were sealed include the five components as shown in Figure 1, namely the front and back rotation crease, the front and back grill and the air filter.

The first leakage flow rate vs. pressure drop data that was collected was for a fully "sealed – least leak" configuration of the dryer, and this was used as a benchmark for

comparison to all other sealed configurations, with one exception – the air filter. The air filter is connected to the air circulation duct; if the front and back grill are sealed, air cannot flow through the air filter. With the exception of the air filter, each of these components was unsealed individually. The difference between the increased leakage area corresponding to unsealed configurations (i.e. unsealed front crease only, back crease only, front grill only, and back grill only) and the baseline fully "sealed – least leak" leakage area yields the individual contribution of that component to leakage. The difference in leakage area corresponding to unsealing the air filter and the leakage area corresponding to unsealing the front and back grills is the contribution associated with the air filter.

5. RESULTS AND DISCUSSION

Prior to sealing components, it was observed that rotating the dryer drum led to different leakage volumetric flow rates for the same drum pressures. The wavy baffle in the dryer drum was assigned a value of 0 degrees at an arbitrary initial position and was rotated through 90, 180 and 270 degrees. Unsealed leakage tests were performed at each of these rotations. A volume flow rate vs. pressure curve was generated for each of these rotations and these curves are given in Figure 4. The elliptical shape of the drum is the likely cause of the discrepancy in leakage at the various angles of rotation. Different parts of the drum were exposed to the damaged gasket and the air duct as the drum was rotated, affecting the leakage volumetric flow rate. Since the 270 degree rotation yielded the largest flow, all tests were performed at that rotation.

Following this, the dryer components were fully sealed and each component was unsealed one-by-one. At all times, only one component was unsealed. This allowed comparison to the best "sealed – least leak" case scenario. The current method of analyzing each component individually and comparing them to the same baseline minimizes sensitivity and error issues, and

also allows the determination of the front and back rotation crease leakage separately. It has also been verified that the front and back grill do not contribute to drum leakage, but they are responsible for duct leakage.

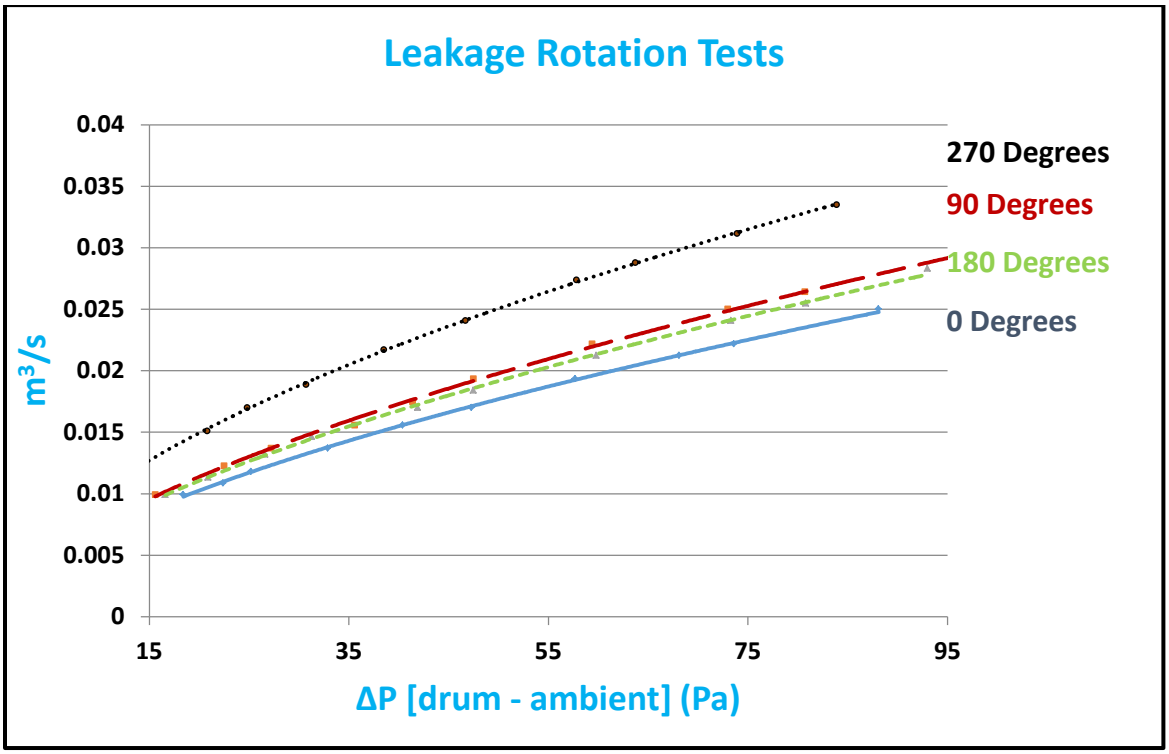

Figure 4: Leakage flow rate ($\frac{m^3}{s}$) vs. ΔP- Unsealed leakage corresponding to various drum rotation angles

To determine the contribution of each component to leakage, initially the drum and the duct were completely sealed. That yielded the best "sealed – least leak" case scenario, from which every leakage area contributor was compared against. This may be referred to as the "*miscellaneous losses*". Only one of the mentioned components was unsealed at a time to isolate their leakage area contribution. An exception here is the air filter, due to the fact that the duct system (the front and back grill) must be open to allow air flow through the filter. In this case,

the air filter leakage was compared to the front and back grill leakage. The drum components were unsealed first, followed by the air filter.

Figure 5 shows the results of the leakage volumetric flow rate vs. pressure drop tests. The trends generally follow as expected – the unsealed configuration curve is located above all other curves, and the fully sealed configuration curve lies below all curves. One notable observation is the leakage curve for the front grill did not change after additionally unsealing the back grill. This supports the claim that the front and back grill connect to the same leakage points. In either configuration, air flows to the same leakage points in the air circulation duct, and the physical leakage area is not affected. Another observation is that even when all components are fully sealed, there is still some leakage reported. There are regions outside the drum where air flow can be felt, however, they are deep inside the dryer housing and cannot be accessed unless the housing is taken apart. It is currently unknown where these leakage points are located. However, it is very likely that the leakage is from the drum and not the air circulation duct because air flow is cut off to the duct when the front and back grill are sealed.

The coefficients for Equation (1), generated from the regression analysis, the calculated effective leakage areas, using Equation (3), and the measured leakage areas, using the DG-700 device, are given in Table 1. The best "sealed – least leak" case scenario yielded an effective leakage area of 0.001 m^2, and this leakage is associated with the drum. Unsealing the front rotation crease (Table 1, Case 1) increased the area to 0.0015 m^2, whereas unsealing the back rotation crease (Table 1, Case 2) increased the area to 0.0020 m^2. Unsealing the front grill (Table 1, Case 3) only increased the area to 0.0015 m^2, and there was no change when additionally unsealing the back grill (Table 1, Case 4). The back grill was not unsealed alone because the standard air flow during operation flows out from the back grill, rather than in, which would be

caused by pressurizing the drum. Unsealing the air filter (Table 1, Case 5) was followed by an increase in leakage area to 0.0019 m^2. These results suggest that drum leakage is greater than the duct leakage. Finally, as noted earlier, the K values were corrected to 1 for leakage areas measured with the DG-700. This correction results in effective leakage areas that are in close agreement as calculated with Equation (3) and measured with the DG-700. Figure 6 displays these results graphically.

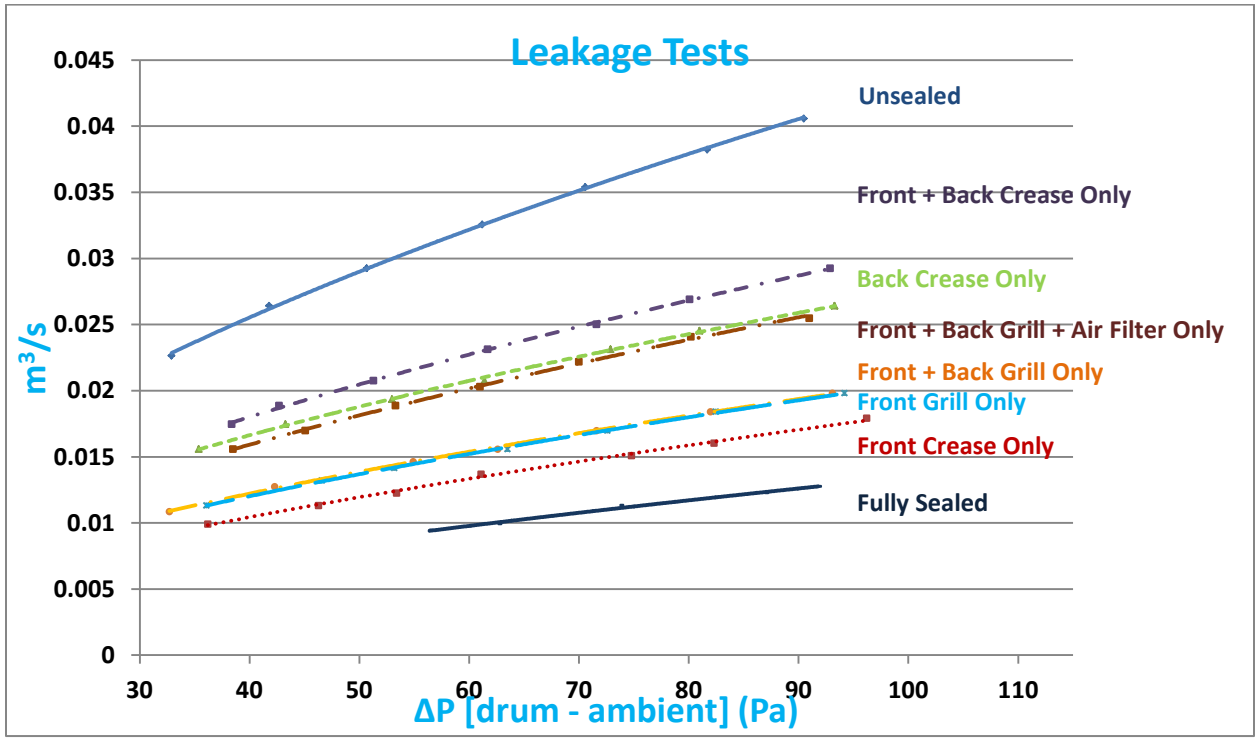

Figure 5: Leakage volumetric flow rate ($\frac{m^3}{s}$) vs. drum pressure drop (Pa) for sealing of various HPCD components.

Table 1: Regression Coefficients and Effective Leakage Areas

Parts Unsealed	c	n	Calculated area [m²], 50 Pa	Measured area, K = 0.61, [m²], 50 Pa	Measured area, K = 1, [m²], 50 Pa
1. Fully sealed	0.0008	0.6269	0.0010	0.0016	0.0010
2. Front rotation crease only	0.0011	0.605	0.0013	0.0022	0.0014
3. Back rotation crease only	0.0022	0.5453	0.0020	0.0034	0.0021
4. Front and back crease only	0.0022	0.575	0.0023	0.0037	0.0023
5. Front grill only	0.0014	0.5823	0.0015	0.0025	0.0015
6. Front and back grill only	0.0015	0.5685	0.0015	0.0025	0.0015
7. Front and back grill, air filter only	0.0018	0.5836	0.0019	0.0033	0.0020
8. None/fully unsealed	0.0031	0.57	0.0031	0.0053	0.0032

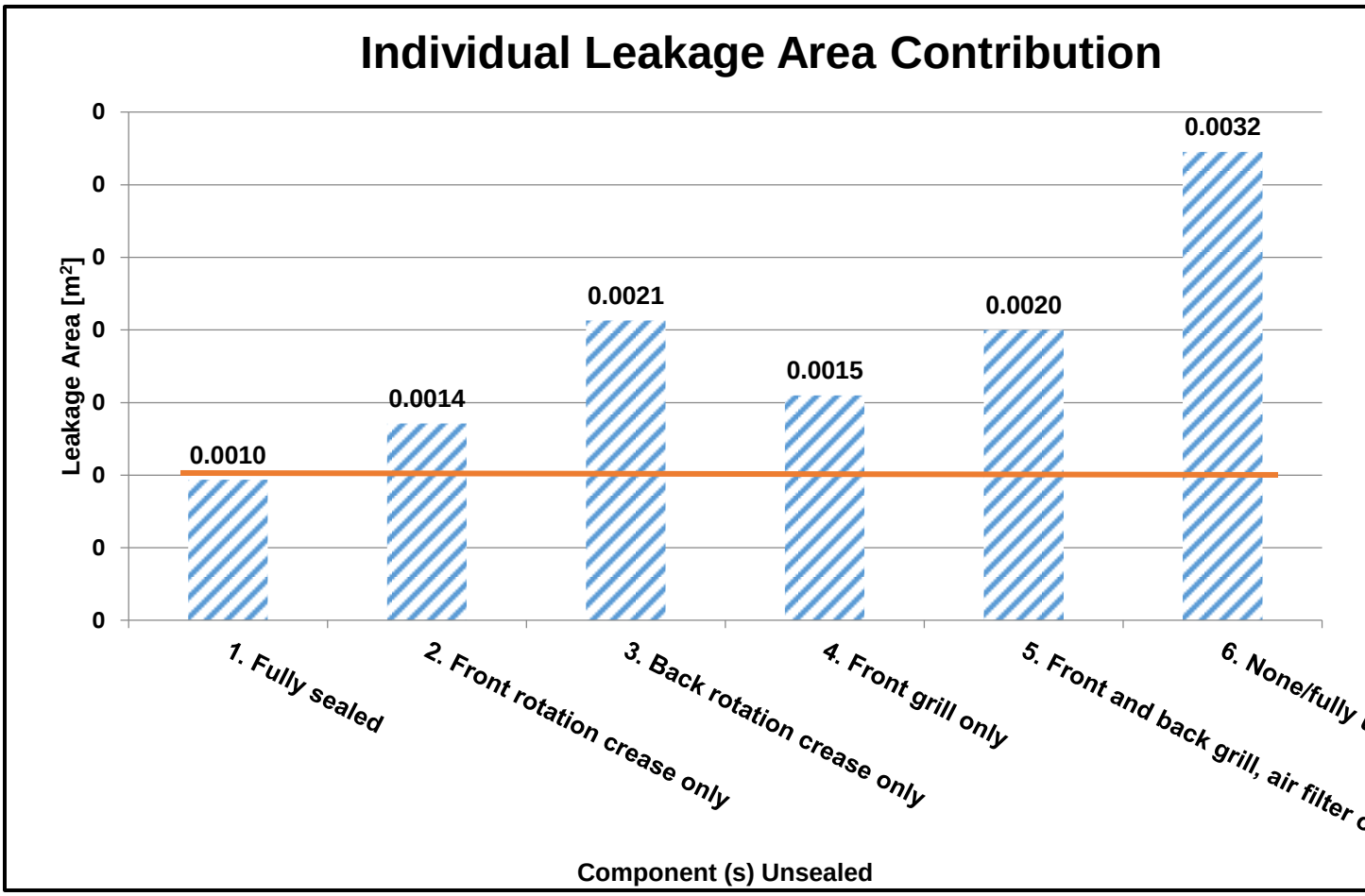

Figure 6: Leakage area attributed to various HPCD components.

One decimal place on area was reported because the pressure reading from the DG - 700 gauge only displayed one decimal place. The front rotation crease discrepancy gave the worst error of 5% due to the low numerical quantities however 0.1 is the worst that any value is off by.

Five independent leakage locations were isolated from these results, which include: the front and back rotation crease, the front grill/duct, the air filter, and the remainder of the drum (components 2, 3, 5, 7 and 8 respectively, illustrated in figure 1). The leakage area and the percentage of total leakage area for these five components are given in Table 2. Figure 7 shows these percentages graphically, while Figure 8 displays the same results by showing specific contributions due to drum leakage and duct leakage. These percentages were calculated as mentioned in the methods section, by the difference in their respective areas from the fully sealed configuration, with the exception of the air filter (which was calculated as mentioned in the methods section). These individual leakages were normalized to their combined sum. Table 2 shows the actual values for these areas. The calculated areas from Equation (3) were used to calculate these differences and percentages.

Table 2: Individual Component Leakage

Point of Leakage	Leakage Area [m²]	Percentage of total Leakage
Miscellaneous/ Drum	0.0010	28
Front rotation crease	0.0004	11
Back rotation crease	0.0011	31
Front grill/Duct	0.0006	17
Air Filter	0.0005	13
Total	0.0035	100

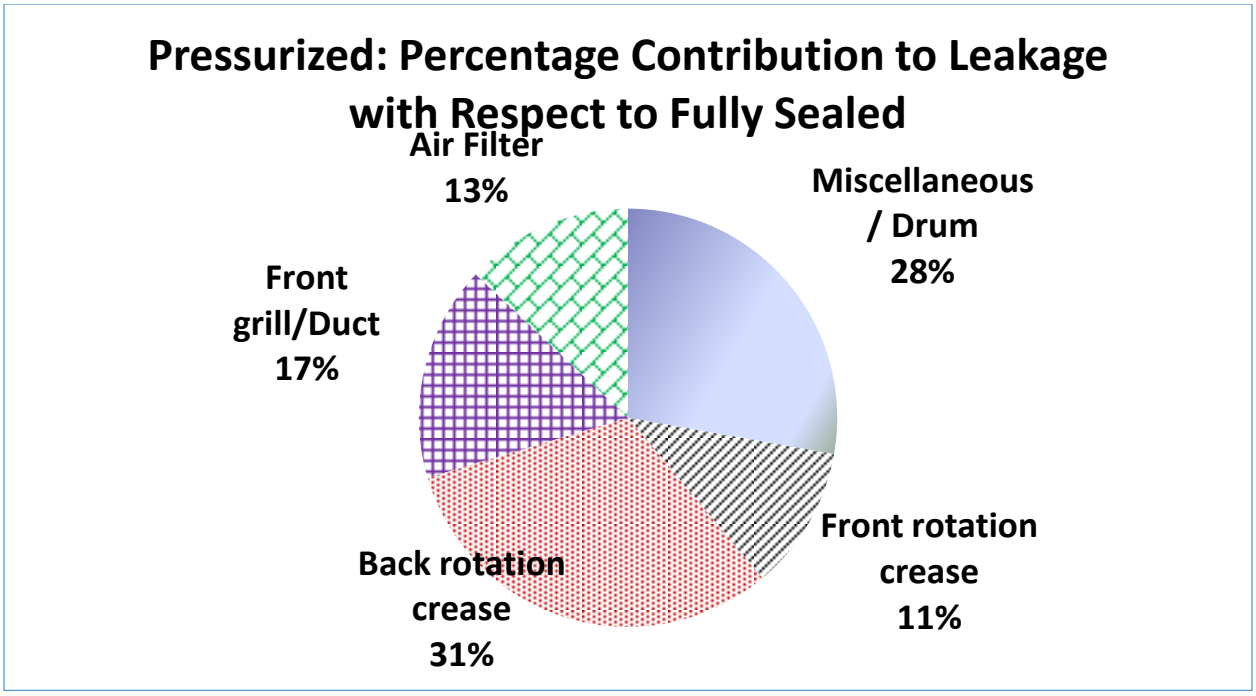

Figure 7: Contribution to total leakage area for various components.

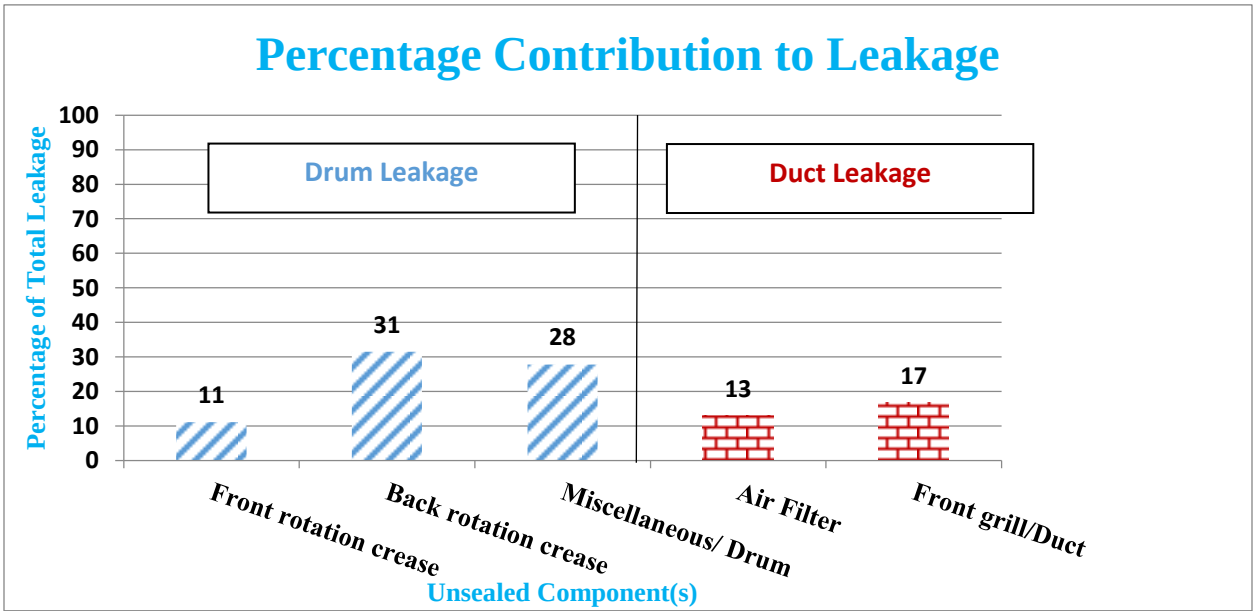

Figure 8: Percentage contributions to leakage after components were unsealed.

Comparing values from Tables 1 and 2, a discrepancy can be noted between the total leakage and the fully unsealed leakage. Table 1 displays a measured value of 0.0031 m^2 (configuration 1), while Table 2 displays a calculated value of 0.0035 m^2, a 13% deviation from the former. There are two possibilities for this discrepancy: (1) the non-linear nature of the pressure volume correlation (2) sensitivity error of the device.

The purpose of configuration 4 (front and back rotation crease unsealed together) was to compare individual leakages of these components to their combined leakages. There is also a discrepancy here, as shown in Table 3. Individually, the unsealed front and back rotation creases add up to an area of 0.0015 m^2, whereas unsealing the front and back rotation creases together yields an area of 0.0023 m^2. This indicates that there may be some overlap in leakage between the front and back crease.

Table 3: Leakage Areas for Configurations 2, 3 and 4

Components Unsealed	Leakage Area [m²]
Front rotation crease	0.0004
Back rotation crease	0.0011
Total	0.0015

6. CONCLUSIONS

This method successfully displays a decrease in effective leakage area after sealing various dryer components. Even if the ELA is not the actual value, it is a reasonable estimate on proportional decrease as a result of sealing components, thus the most reliable parts of the experiment are percentage leakage contribution for various configurations. The leakage coefficients for Equation (3) vary for each configuration and are always constant for Equation (4), yet agree, at worst,

within a margin of 5%. This supports extension of this ASTM method to dryer leakage testing. At the very least, this method can be used to determine relative leakage. Easily accessible leakage points were quantified: the front and back crease, the leakage in the duct, the air filter, and the remaining leakage in the drum. The concordance of results indicates that our method estimates the leakage area reasonably well.

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