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

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ABSTRACT

Although heat pump clothes dryers offer the potential to save a significant amount of energy as compared to conventional vented electric dryers; they are prone to air leakage that can limit their efficiency gain. 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 method follows an American Society of Testing and Materials (ASTM) standard, which is used to determine air leakage area in a household ventilation system through fan pressurization. This ASTM method is adapted to the dryer system, and the leakage area is determined by an analysis of the leakage volumetric flow - pressure relationship. The procedure presents a framework that determines and quantifies major components contributing to leakage in HPCDs. The novel method can improve component design features, resulting in more efficient HPCD systems.

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

Nomenclature

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

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1. INTRODUCTION

Heating of air is an expensive process that uses primary energy in all types of clothes dryers. The majority of clothes dryers (about 80%) in U. S. households are vented electric dryers [1], where air flows in an open cycle. The air undergoes three specific cycles- (i) air is heated by an electric heater, (ii) air enters the clothes drum absorbing moisture from wet clothes, and (iii) the hot moist air is exhausted outdoors by a fan from the dryer. This results in about 40% of the applied heat being wasted in the form of an elevated exhaust temperature [2]. In a heat pump clothes dryer (HPCD), shown in Figure 1, the air is circulated in a closed loop without the need of any exhaust ducting and most of the heat is retained inside the cycle.

The vapor compression heat pump cycle of a HPCD consists of four main components- an evaporator, a compressor, a condenser and an expansion valve. The air duct houses the evaporator and condenser of the refrigeration cycle (see Figure 1). The cycle operates in a closed loop where moist air from the drum flows in the air duct over the evaporator, where it is dehumidified. The resultant condensed water at the evaporator is collected in a pan which is drained at five-minute intervals by a pump. The dehumidified air then flows over the condenser of the heat pump cycle, where it is sensibly heated and flows back into the dryer drum to complete the cycle. Due to the recycling of heated air, a heat pump clothes dryer offers the potential to save 60% of energy as compared with the conventional vented electric dryers [3].

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% of the total air volumetric flow [2]), resulting in a loss of efficiency. Stawreberg et al. [4] noted that there is considerable leakage through the gap between the heater and the drum inlet and between the heat exchanger and the heater in a condensing tumbler dryer. Bansal et al. [5] assumed

upwards of 20% leakage of the total air volumetric flow in their modeling studies. An easy way to maximize the energy efficiency of a HPCD is to make the air circulation system relatively leak-tight. 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 [5-19] in the open literature, the leakage aspect of specific parts of the dryer has never been studied in detail previously. So far, efforts have primarily focused on analyzing the energy efficiency of HPCDs [5, 11, 13, 15, 16], while only the overall leakage has been documented in one study [2]. Knowledge of specific leakage points offers the necessary information to minimize the amount of leakage in the air cycle, providing information for the best design possible. Hence this study serves to develop a novel method for quantifying leakage from HPCDs, and subsequently, tests this method on easily accessible specific leakage locations in the dryer drum and air circulation system.

2. AIR LEAKAGE TEST PROCEDURE

The basis of the proposed clothes dryer air leakage test method is the American Society of Testing and Materials (ASTM) standard E779 – 10 that allows determining the air leakage area in a household ventilation system through fan pressurization [20]. This ASTM method is readily adaptable to the dryer system because the leakage measurement process is the same as a ventilation system. The dryer system is pressurized just as a ventilation system, and flow rates are measured to determine leakage. The leakage area is determined following the leakage volumetric flow and pressure relationship provided in E779-10 [21]. A Minneapolis Duct Blaster [22] is used to pressurize the dryer drum and an accompanying pressure and flow gauge (DG – 700) is used to measure the duct blaster air flow rate and drum pressure drop. The DG - 700 is a

calibrated sensor from the same manufacturer that measures the Minneapolis Duct Blaster's flow rate from the pressure drop along the fan. The information on measurement uncertainties is presented in section 3. The duct blaster pressurizes the dryer drum. A pressure tap is fed to the dryer drum, and the DG - 700 records the pressure caused by the duct blaster in that region. 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 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 drum that contribute greatest to its leakage are the front rotation crease, and the back rotation crease. Both of these parts allow the drum to rotate, and must have the proper spacing to do so. Hence it is likely that these parts are the largest contributors to air leakage in the drum. There are three different types of baffles along the drum of the dryer, all of which are accessible for sealing. There are small creases exposed on all baffles. The baffle filter has a removable filter, thus, has the likelihood of leakage. The wavy baffle and oval baffles are shaped as they are named, but do not have any filters attached to them. Their function is to add extra tumbling on clothes during the dryer cycle. The air circulation duct is not easily accessible; however the parts that have been observed to lead 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.

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:

$$Q = C(\Delta P)^n \quad (1)$$

In Equation (1), C and n are determined through a regression analysis of the pressure drop and volumetric flow data points.

Since leakage points are hypothesized to occur through manufacturing defects, they are physically small in cross sectional area, and therefore can be approximated as orifices. Thus, the following relationship between leakage volumetric flow rate and drum pressure drop may be used to estimate the HPCD leakage:

$$Q = K A_o \sqrt{\frac{2\Delta P}{\rho}} \quad (2)$$

Equation (2) is the orifice equation derived from Bernoulli's principle of flow along a streamline, neglecting changes in potential energy. Combining Equations (1) and (2) yields Equation (3) for calculating the effective leakage area (ELA) of all points:

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

Note that the ASTM standard assumes that all orifice lengths are negligible, thus the value of K is 1¹. Furthermore, adapting Equation (3) to the dryer system requires the following assumptions:

¹ Effective leakage area, ELA, used herein is documented in ASTM E 1827, the formulation in Eq 3 differs from a similar measure of airtightness that uses the same reference pressure but assumes a discharge coefficient [23].

- 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.
- 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 can be 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 after achieving steady state, and the only other pressure region is the ambient pressure. Therefore this pressure gradient provides the driving force for the leakage or air.

The DG - 700 gauge used to measure the volumetric flow rate and drum pressure drop determines the effective leakage area at a reference pressure of 50 Pa based on the following empirical correlation given in the DG - 700 manual [20, 21]:

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

The most accurate results are obtained with the duct blaster and DG-700 when the test pressure, P^* , is 50 Pa [21]. 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 [20]. At a ± 5 Pa range from the ideal test pressure of 50 Pa, the uncertainty on the DG-700 gauge is at most 1% in n [21]. Table 1 displays uncertainties for a range of n corresponding to different test pressures [21]. The effect of this is very small on the volumetric flow rate and is assumed to be negligible. 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).

Table 1: DG - 700 Uncertainties in n as a Function of P^* for the 50 Pa Mode

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, is used to measure the fan volumetric flow rate while simultaneously measuring the drum pressure drop. An outline of the measurement principle was presented in section 2. The duct blaster incorporates a variable speed fan [20], which has three inlet rings of varying inner diameter that attach to its inlet to provide a range of volumetric flow rate 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 two regions where the pressure was measured included the fan inlet and the dryer drum. A static pressure tap was installed in the drum. Both pressure measurement regions were connected to the DG - 700 gauge using plastic tubing. Both channels are referenced to 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. Data was recorded for seven different pressure drops from which the leakage volumetric flow rate was reduced and recorded. The data was subsequently plotted and a power regression was performed for each sealed configuration to calculate an effective leak 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. The fully unsealed case gives the leakage of the dryer as it comes out of the manufacturer. During initial testing, it was determined that the contribution of baffles to leakage was insignificant, therefore they were not considered in the air leakage analysis. The five

components that were sealed are shown in Figure 1, namely the front and back rotation crease, the front and back grill and the air filter.

The first set of leakage flow rate vs. pressure drop data 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. unsealing the front crease only, the back crease only, the front grill only, and the 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. Though the cause of this discrepancy is not fully known, it is attributed to manufacturing defects and wear of the dryer over time. The dryer has been extensively tested

during the last few years and hence it is likely that this may have caused some internal damage. Since the 270 degree rotation yielded the largest flow, all tests were performed at that rotation.

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 all component 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. The best "sealed least-leak" scenario 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. However, the air filter is an exception 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 with the front and the back grill leakage that results in the air filter leakage. The drum components were unsealed first, followed by the air filter.

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

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 actual leakage area is not affected. Another observation is, 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.

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

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 2. The best “sealed – least leak” case scenario yielded an effective leakage area of 0.0010 m^2 , and this leakage is associated with the drum. Unsealing the front rotation crease (2) increased the area to 0.0014 m^2 , whereas unsealing the back rotation crease (3) increased the area to 0.0021 m^2 . Unsealing only the front grill (5) only increased the area to 0.0015 m^2 , and there was no change when additionally unsealing the back grill (6). Unsealing the air filter (7) was followed by an increase in leakage area to 0.0020 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, where the horizontal solid ‘red’ line across the graph at the leakage area of 0.0010 m^2 displays the best ‘sealed – least leak’ case for easy comparison with other cases.

Table 2: Regression Coefficients and Effective Leakage Areas

Figure 6: Leakage area attributed to various HPCD components.

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 3. The calculated areas from Equation (3) were used to calculate these differences and percentages.

Table 3: Individual Component Leakage

Comparing values from Tables 2 and 3, a discrepancy can be noted between the total leakage and the fully unsealed leakage. Table 2 displays a measured value of 0.0032 m^2 (configuration 1), while summing up all individual component leakages in Table 3 results in a value of 0.0034 m^2 , a 6% deviation from the former. As mentioned in the theory section, the uncertainties using a test pressure of 50 Pa does not significantly affect the measured values. Thus cause of this discrepancy is likely to be the non-linear nature of the pressure volume correlation.

The purpose of configuration 4 (front and back rotation crease unsealed together) was to compare individual leakages of these components to their combined leakages. This displays another discrepancy, shown in Table 4. 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 0.0013 m^2 . This indicates that there may be some overlap in leakage between the front and back crease.

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

This is only an empirical observation and the actual relationship between the two (if at all) is unknown. According to Table 1, the worst error on the pressure exponent is on the order of 20%, which comes from a test pressure of 10 Pa. Applying this to all of these parts (including the fully unsealed configuration which is used in calculating individual leakage comparisons) yields the following ranges: 0.0002 - 0.0004, 0.0007 - 0.0014, 0.0008 - 0.0019 for the front crease, back crease and combined two respectively. In actual measurements however, variation in the pressure exponent will be at most 1% which does not affect these values. Therefore the discrepancy here cannot be attributed to uncertainty, and a further investigation would be needed to determine the coupling of leakage on these components.

This method determines large leakage points, but is limited in determining specific parts, especially when the leakage differences are small. The process of sealing could be more robust; in this experiment sealing was done by taping openings with duct tape. An alternative is to build panels for each component that can quickly connect and disconnect. Further, the next step would be to analyze leakage components that are not easily accessible.

It is concerning that there is still leakage observed in the fully sealed case, and mitigating these leaks are unavoidable with this current method of sealing, which suggests problems in the manufacturing process. By observation of a change in the leakage area measurement, the controllable leak regions thus far are the front and back rotation crease, the air filter and the front grill. It is difficult to quantify any leakages in the duct system without taking apart the dryer. This suggests that there is room for the manufacturing process to create a more leak tight air duct system.

Though the experiments were performed in steady state flow, the startup and cooling down period of a dryer cycle were not steady. If there is significant leakage in the HPCD, it is likely that repeatedly heating and cooling regions of leakage could affect leakage area due to constant agitation of that region. Unfortunately, this method can only be implemented on a dryer when it is not in operation, and thus cannot directly measure the effect of leakage during a transient process. Nonetheless, even if the effective leakage area (ELA) is not the actual value, it is a reasonable estimate on proportional decrease as a result of sealing components, due to repeatability, thus the most reliable parts of the experiment are percentage leakage contribution for various configurations.

6. CONCLUSIONS

This paper presents a novel method to determine air leakage in HPCDs that repeatedly displays a decrease in effective leakage area after sealing various dryer components. The research presents a framework to detect and quantify air leakage in a HPCD system, and, in general can be applied to any system that contains air leakage through defects that are approximately orifices, so long as the pressure gradient driving the leakage can be measured. The leakage coefficients for Equation (3) vary for each configuration and are always constant for Equation (4). The worst comparison between the predicted leakage area and the measured area is within margin of 7%. This supports extension of the ASTM E779 - 10 method to dryer leakage testing and can be used to determine, at the least, 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.

ACKNOWLEDGMENTS

The authors are thankful to the Building Technologies Office of the US Department of Energy for their financial support and industry partner General Electric Appliances for their kind and technical support. Special thanks are due to a number of contributors for their invaluable contributions and support during this project, including Mr. Edward Vineyard, Dr. Bo Shen, Dr. Kyle Gluesenkamp, Dr. Keith Rice, Mr. Van Baxter, Mr. Phillip Boudreaux, Mr. Jerry Atchley, Mr. Randall Linkous, Mr. Neal Durfee, Mr. David Beers, Mr. Zhiquan Yu and Quentin Pollett.

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

Figure 2: Schematic of experimental setup

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

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

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

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Figure 6: Leakage area attributed to various HPCD components.

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Table 1: DG - 700 Uncertainties in n as a Function of P^* for the 50 Pa Mode

		Actual Pressure Exponent " n "					
		0.5	0.55	0.6	0.65	0.7	0.75
Test Pressure Values, P^*	10	21.4%	14.9%	7.7%	0.0%	-8.4%	-17.5%
	15	16.5%	11.3%	5.8%	0.0%	-6.2%	-12.8%
	20	12.8%	8.8%	4.5%	0.0%	-4.7%	-9.6%
	25	9.9%	6.7%	3.4%	0.0%	-3.5%	-7.2%
	30	7.4%	5.0%	2.5%	0.0%	-2.6%	-5.2%
	35	5.2%	3.5%	1.8%	0.0%	-1.8%	-3.6%
	40	3.3%	2.2%	1.1%	0.0%	-1.1%	-2.3%
	45	1.6%	1.0%	0.5%	0.0%	-0.5%	-1.1%
	50	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	55	-1.4%	-1.0%	-0.5%	0.0%	0.5%	0.9
	60	-2.8%	-1.8%	-0.9%	0.0%	0.9%	1.8%
	65	-4.0%	-2.7%	-1.3%	0.0%	1.3%	2.6%

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Table 2: Regression Coefficients and Effective Leakage Areas

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

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Table 3: Individual Component Leakage

Point of Leakage	Leakage Area [m ²]	Percentage of total Leakage
Miscellaneous/ Drum	0.0010	28
Front rotation crease	0.0004	11
Back rotation crease	0.0011	31
Front grill/Duct	0.0005	17
Air Filter	0.0005	13
Total	0.0034	100

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

Components Unsealed	Leakage Area [m ²]
Front rotation crease	0.0004
Back rotation crease	0.0011
Front and back together	0.0013

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