

High Efficiency, High Performance Clothes Dryer

Final Report to: Department of Energy

Reporting Period - 9-30-01 – 3-31-03

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March 31, 2005

Contract Number DE-FC26-01NT41260

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Abstract

This program covered the development of two separate products; an electric heat pump clothes dryer and a modulating gas dryer. These development efforts were independent of one another and are presented in this report in two separate volumes. Volume 1 details the Heat Pump Dryer Development while Volume 2 details the Modulating Gas Dryer Development. In both product development efforts, the intent was to develop high efficiency, high performance designs that would be attractive to US consumers. Working with Whirlpool Corporation as our commercial partner, TIAX applied this approach of satisfying consumer needs throughout the Product Development Process for both dryer designs.

Heat pump clothes dryers have been in existence for years, especially in Europe, but have not been able to penetrate the market. This has been especially true in the US market where no volume production heat pump dryers are available. The issue has typically been around two key areas: cost and performance. Cost is a given in that a heat pump clothes dryer has numerous additional components associated with it. While heat pump dryers have been able to achieve significant energy savings compared to standard electric resistance dryers (over 50% in some cases), designs to date have been hampered by excessively long dry times, a major market driver in the US.

The development work done on the heat pump dryer over the course of this program led to a demonstration dryer that delivered the following performance characteristics:

- 40-50% energy savings on large loads with 35°F lower fabric temperatures and similar dry times
- 10-30°F reduction in fabric temperature for delicate loads with up to 50% energy savings and 30-40% time savings
- Improved fabric temperature uniformity
- Robust performance across a range of vent restrictions

For the gas dryer development, the concept developed was one of modulating the gas flow to the dryer throughout the dry cycle. Through heat modulation in a gas dryer, significant time and energy savings, combined with dramatically reduced fabric temperatures, was achieved in a cost-effective manner. The key design factor lay in developing a system that matches the heat input to the dryer with the fabrics' ability to absorb it.

The development work done on the modulating gas dryer over the course of this program led to a demonstration dryer that delivered the following performance characteristics:

- Up to 25% reduction in energy consumption for small and medium loads;
- Up to 35% time savings for large loads with 10-15% energy reduction and no adverse effect on cloth temperatures;

- Reduced fabric temperatures, dry times and 18% energy reduction for delicate loads; and,
- Robust performance across a range of vent restrictions

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Executive Summary

Laundry areas in homes are moving out of the basement. The trend in many newer homes is to integrate complete laundry centers into the home's living space, typically at a considerable expense. Combining this trend with a greater awareness of energy conservation, especially water conservation, has led to a significant increase in market share of high-end front loading washing machines with many consumer-focused performance attributes. Meanwhile, in general, the clothes dryer has changed very little. With this market condition as a backdrop, a product development program was undertaken to develop high efficiency, high performance gas and electric clothes dryers for the US market. TIAX, along with our commercial partner Whirlpool Corporation, applied a rigorous Product Development Process to the development of two separate dryer designs; a heat pump clothes dryer and a modulating gas dryer.

The first step in the product development process was to understand the marketplace for such products. Extensive consumer feedback focus group studies were performed in the Boston, Chicago and San Jose areas in order to better understand consumer wants and desires with respect to laundry. The primary objective of this consumer feedback work was to quantify the relative importance of energy use, time to dry and purchase cost to consumers of gas and electric clothes dryers. This consumer focus group work provided the foundation from which the rest of the product design process was constructed.

For the heat pump dryer, the product development effort was spread across four key tasks:

- Developing the initial design;
- Fabrication and testing of an initial prototype;
- Development and testing of a validation unit; and
- Development and testing of a demonstration unit.

Whirlpool identified their ADOTT dryer with pedestal as the basis from which the heat pump dryer was to be constructed. This selected dryer platform bracketed the geometrical limitations of the dryer and the boundaries in which the heat pump unit had to fit. This line of dryers represents Whirlpool's premium dryer line.

In developing and refining the design, the following five key steps were performed:

- Development of a detailed product specification to meet the consumer's needs;
- Developing the necessary capacity to meet those specifications;
- Developing a system design that optimized the capacity of the heat pump;
- Developing a sensors and controls approach to apply to the design; and,
- Extensive product testing to demonstrate performance.

The end result was a heat pump clothes dryer that had the following attributes:

- 40-50% energy savings on large loads with 35°F lower fabric temperatures and similar dry times
- 10-30°F reduction in fabric temperature for delicate loads with up to 50% energy savings and 30-40% time savings
- Improved fabric temperature uniformity
- Robust performance across a range of vent restrictions

For the modulating gas dryer, the product development process had as its basis work done by TIAX on a previous program for Whirlpool Corporation to develop a prototype modulating design. From this advanced starting point, the remaining effort was spread across five key tasks:

- Developing detailed gas system design;
- Fabrication and testing of a refined prototype;
- Development and testing of a validation unit;
- Development and testing of a verification unit; and
- Development and testing of a demonstration unit.

As with the electric dryer, Whirlpool identified their ADOTT dryer as the basis from which the modulating gas dryer was to be constructed. This dryer platform bracketed the geometrical limitations of the dryer and the boundaries in which the necessary components had to fit.

In developing and refining the design, the following five key steps were performed:

- Development of a detailed product specification to meet the needs of the marketplace;
- Identifying and delivering the necessary gas input rates to meet the specifications;
- Delivering the proper airflow for modulation and venting variations;
- Developing a sensors and controls approach; and
- Extensive product testing to demonstrate performance

The end result was a modulating clothes dryer that had the following attributes:

- Up to 25% reduction in energy consumption for small and medium loads;
- Up to 35% time savings for large loads with 10-15% reduction in energy consumption and no adverse effect on cloth temperatures;
- Reduced fabric temperatures, dry times and 18% energy reduction for delicate loads; and,
- Robust performance across a range of vent restrictions.

For both designs, detailed CAD drawings and product and component specifications were developed and handed over to Whirlpool Corporation for commercialization. Both designs are currently progressing through Whirlpool's internal Concept to Commercialization Process.

Volume 1 – Development of a Heat Pump Dryer

1.0 Introduction

Laundry areas in homes are moving out of the basement. The trend in many newer homes is to integrate complete laundry centers into the living space, typically at a considerable expense. Combining this trend with a greater awareness of energy conservation, especially water conservation, has led to a significant increase in market share of high-end front-loading washing machines with many consumer-focused performance attributes. Meanwhile, in general, the clothes dryer has changed very little.

At the start of this program, extensive consumer feedback focus group studies were performed in the Boston, Chicago and San Jose areas in order to better understand consumer wants and desires with respect to laundry. The primary objective of this consumer feedback process was to quantify the relative importance of energy use, time to dry and purchase cost to consumers of gas and electric clothes dryers. Specifically, the following areas were explored:

- Consumer sensitivity to energy issues and perceived value of energy savings;
- Consumer response to different descriptions of energy opportunities (i.e. response to potential approaches to marketing energy savings);
- Consumer sensitivity to dry time and desired relationship between dry time and wash time;
- Impact of key dryer features and functionality on the likelihood of purchase.

It was determined that current owners of electric clothes dryers were willing to pay significantly more to achieve energy savings, however cost sensitivity varied by location. In addition, the following results were gathered from these focus group activities:

- Consumers were skeptical of claims of significant levels of energy savings. In general, they were not willing to pay more for 60% energy savings than they were for 40% savings;
- The top three purchase criteria for clothes dryers were listed as reliability, features and functions, and price;
- Consumer interest in energy efficiency is not tied to payback but more to a desire to do what is environmentally sound;
- Waiting for the dryer to finish its cycle was considered to be one of the most time consuming laundry tasks;
- Dry times are extremely important. Consumers were not willing to pay a price premium for a high-efficiency dryer if it meant longer dry times;
- Participants withhold as much as 50% of their clothes from the dryer from fear of cloth damage, mainly due to excessive heat;
- Having a dryer which is an “all fabric” dryer (which the heat pump would be) was very attractive to consumers;

- Consumers do not see benefits associated with a vent-free dryer and would be wary of installing such a unit in their homes.

With this market information as a starting point, work began on developing a heat pump dryer that could meet these market needs.

1.1. Developing a Dryer to Meet the Market Needs

Heat pump dryers traditionally do a very good job of delivering significant energy savings, but tend to have very long dry times. The heat pump dryers that were found on the market in Europe deliver on the promise of significant energy savings, but their dry times were significantly longer than those associated with standard US electric dryers. In some cases, the dry time for a large load was almost twice as long in a heat pump dryer as it is in a standard US electric dryer. In order to address the consumer needs and develop an energy efficient heat pump dryer that delivered reasonable dry times, a new approach was needed.

Most standard electric dryers on the market today operate with a heating element at a fixed wattage and a fixed airflow rate (varying only in response to load size and venting configurations that create the system pressure drop). The element typically operates in an on/off mode as determined by the cycle chosen and the temperature of the exhaust flow. Many dryers integrate a type of moisture sensor, the most common being conductivity strips, to assist in identifying when to terminate a cycle. These strips serve to measure gross detection of whether the load is wet or not and typically do not provide much indication of how wet or how dry.

In order to develop a heat pump dryer that is acceptable to the US marketplace, three key areas need to be addressed:

- 1) The capacity needed to deliver the necessary dry times must be defined;
- 2) A system needs to be developed that optimizes the available capacity and applies it in an effective manner;
- 3) A sensors and controls system needs to be implemented that properly controls the heat pump system and maximizes its benefits.

1.2. Defining the necessary capacity to achieve time reduction

In defining the necessary heat pump system design requirements, four key areas need to be considered:

- 1) Refrigerant selection;
- 2) Geometry and space considerations;
- 3) Airflow considerations including linting, cloth plastering in the drum and system pressure drops;
- 4) Venting approach.

The key to reducing the dry times associated with heat pump dryers lies in maximizing the inlet temperature and airflow into the dryer's drum. Air temperatures are essentially limited by the choice of refrigerant. Standard R-22 based heat pump systems do not lend themselves to delivering high temperatures. Under the conditions expected in a clothes dryer, maximum R-22 condenser temperatures are around 150°F. To achieve faster dry times, the condenser temperature needs to be higher. In order to achieve the highest possible air temperatures, this design uses R-134a in an R22 AC/Heat Pump compressor. The use of R-134a serves to shift the evaporating and condensing temperatures by 30°F at similar operating pressures and power input. This effect is shown in Figure 1-1.

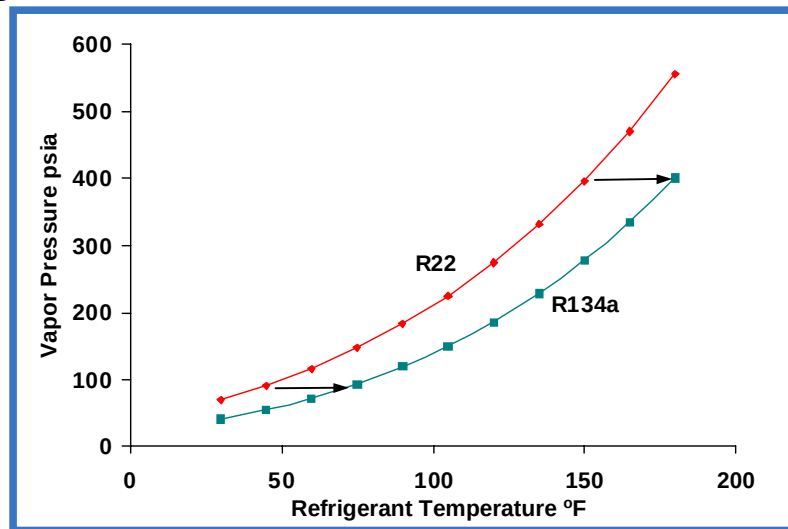


Figure 1-1: Effect of Refrigerant Selection on Condensing Temperatures

By using the R-134a refrigerant, the condensing temperature is shifted from 150°F to 180°F. This results in higher temperatures for the dryer's process air and in turn, faster dry times.

With the selection of the refrigerant in place, the next step was to maximize the capacity of the heat pump system. This means two things. First, the heat exchanger components need to be as large as the available space would allow. Second, the airflow in the system needs to be much higher than those of typical dryers.

Geometry considerations are a significant hurdle in the development of any heat pump dryer. Most of the components associated with the heat pump system (compressor, evaporator, condenser, tubing, etc.) are being added to a dryer cabinet that is already nearly filled by existing components. The design described here had to fit into the existing cabinet space plus a pedestal base. Extensive CAD modeling was done to identify potential layouts and configurations that could maximize the heat exchanger sizing. The heat pump dryer operates as follows. Hot, dry process air enters the rear of the drum and interacts with the clothes in the load. Warm, moist air then exits the drum

and proceeds through the lint screen and through the evaporator where a significant portion of the moisture is removed before flowing through the condenser and back up the rear duct.

In parallel to developing the heat pump layout, airflow system approaches and designs were being considered to maximize the output from the heat pump system. Many aspects affected the design of the airflow system and the approach chosen. These included linting considerations such as heat exchanger face velocities and the effect of increased airflow on cloth plastering in the drum.

In order to maximize the output from the heat pump, significantly higher airflow levels are needed in this design as compared to standard electric dryers. Added to this complication is the fact that the venting approach (described in detail in a later section) is one that is very different than that employed in a standard dryer. These issues lead to the likelihood of lint migration beyond the lint screen into the region of the heat exchangers. While better lint screen alternatives exist, some percentage of lint migration beyond the screen will occur and needs to be managed. This means that the evaporator fins need to be designed in such a way so as to prevent the migration of lint beyond the evaporator face to avoid permanent lint clogging of the evaporator. This affects fin geometry and spacing and dictates maximum allowable face velocity limits. Past manufacturer experience in these areas with condensing and heat pump dryers was utilized in defining the necessary fin geometry and spacing.

Cloth plastering to the outlet grill in the dryer's drum is a significant concern in a high flow heat pump system. Standard dryers operate with approximately 100 cfm of airflow. As the design progressed on the heat pump system, it became apparent that airflows on the order of 250 cfm would be needed to maximize performance. At this flow rate, clothing in the drum being drawn onto the outlet grill and held in place could become a significant issue.

To investigate the effect of flow rate on cloth plastering, a special airflow dryer prototype was constructed. Essentially, this airflow dryer, shown in Figure 1-2, was a standard electric ADOTT dryer that was modified with a much larger, external blower motor configured to deliver significantly higher airflow rates to the drum. Integrated into this dryer were additional heating element capabilities and a venting configuration designed to operate the dryer under similar humidity conditions as those expected in a heat pump system. Four selected clothing loads (delicates, heavy duty, 100% cotton and mixed) were tested at varying airflow rates from 100 to 300 cfm in order to evaluate the plastering effect. Two of these loads are shown in Figure 1-3. The results from these tests are shown in Figure 1-4. Plastering duration was defined as the length of time any piece of clothing resided on the outlet grill. It was determined that in order to avoid plastering, airflow rates needed to be kept below 200 cfm (unless the drum is modified).



Figure 1-2: Airflow Prototype Dryer



Figure 1-3: Example Clothing Loads

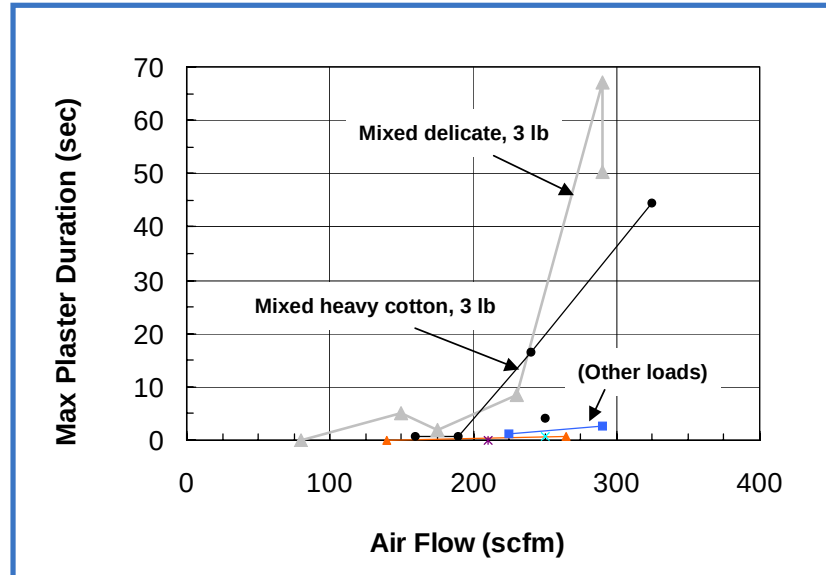


Figure 1-4: Effect of Airflow on cloth plastering to the outlet grill.

This airflow prototype was also used as a means of understanding the performance associated with a heat pump dryer. With the ability to adjust flow rates, heating power and venting configurations, the unit was able to be used as a representation of a heat pump system.

Venting of the heat pump dryer is another key component. Since the evaporator removes the majority of the moisture present in the air exiting the drum, this air can be recirculated back into the drum. Many heat pump dryers use such a ventless design. However, in steady state operation, the heat pump generates more heat than cooling, so some form of heat rejection is needed. Three possible means for this heat removal are:

- an air-to-air heat exchanger in the process air stream to transfer some of the heat to the laundry room
- a post-condenser loop in the refrigerant system so that a portion of the condenser heat is outside the process air stream; or
- an air bleed to introduce room air into the process air and bleed off a portion of the process air into the room.

The alternative to a closed-loop system is to go with an open-loop system where a portion of the process air is vented to the outdoors, similar to a standard dryer. The focus group work had clearly shown a wariness on the part of consumers to a unit that did not have a vent to the outdoors. In addition, the components associated with a closed loop approach would take up valuable space that could be used to gain more heat pump capacity. These factors led to a decision to pursue a partially-open loop design where a portion of the process air is vented outdoors to remove excess heat. Since the

venting is only needed once the system has fully warmed up, a variable venting approach was chosen. With this approach, all of the process air is recirculated through the dryer until the warm-up stage is complete. At that point, the exhaust is opened and a portion of the total flow is vented to the outside. Employing this type of system results in significant energy savings over a fully open loop approach. This is shown in Figure 1-5.

TIAX Benchtop Testing - 12 lb Towels		
Vent Condition	Dry Time, minutes	Energy Consumption (kWh)
Closed Vent During Warmup	58.6	3.58
Fixed Open Vent	60.5	4.05

Figure 1-5: Effect of Venting Approach on Drying Performance

Based on the necessary capacity, geometry considerations, airflow constraints and the chosen venting approach, the specifics of the heat pump design were defined. The design to be implemented in the validation unit was one with 2.2 Kw heat pump power utilizing 250 cfm of airflow. With this design specification in place, work began on developing a system design to optimize the dryer's performance.

1.3. Develop System Design to Optimize Capacity

With the general specification in place for the heat pump system, work began on component selection. The key components in the system include:

- compressor;
- evaporator;
- condenser;
- other refrigerant system components;
- boost heater (if necessary); and
- blower and blower motor

A reciprocating compressor was chosen for the validation unit, mainly for reliability reasons. The pressure ranges under which this design will be operating (in order to maximize condenser temperatures) were such that reciprocating compressors were felt to be more reliable. A rotary compressor design is an alternative option, however additional work would be needed to ensure reliable operation.

With the compressor selection complete, detailed design work began on the heat exchangers. The evaporator design had to be one which was sized for a high latent load. In addition, the evaporator needed to be designed in such a way so as to limit lint migration beyond its inlet face. Extensive heat exchanger modeling was done to

identify the best design. This led to a design that employed multiple circuits and rows in the heat exchanger to minimize pressure drop.

The condenser design needed to be one that maximized heat transfer. An enhanced fin design was chosen in a system design that uses a single circuit employing counterflow circuitry to maximize efficiency. The circuit was also sized with sufficient length to allow for proper sub cooling. Figure 1-6 shows prototype samples of the evaporator and condensers used on the heat pump validation unit.

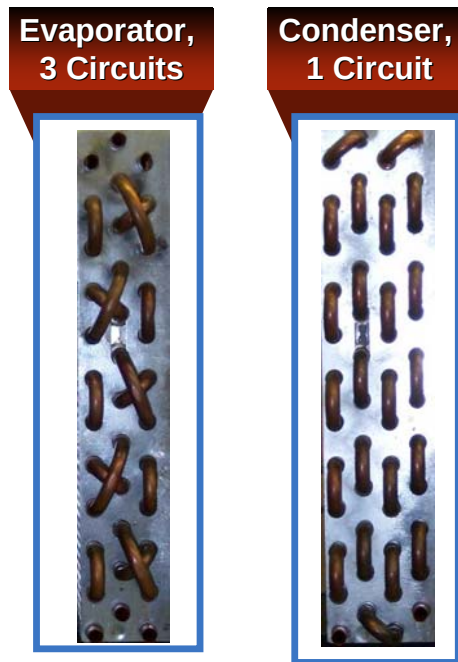


Figure 1-6: Evaporator and Condenser Designs for the Heat Pump Dryer

The total drying process is divided into four phases. These are the warm-up phase, the constant drying rate phase, the falling rate phase and cool down. The moisture removal rate for each of these phases is different. This means the latent load on the evaporator varies throughout the cycle. To account for this variation in heating load throughout the dry cycle, a thermal expansion valve (TXV) was used. The TXV serves to control the refrigerant flow to the evaporator over the different phases of the dry cycle for a wide variety of clothing loads. The resultant performance was low superheat and maximum efficiency for the system. Efficiency was further optimized by charging the system with substantial subcooling at the condenser outlet.

One issue with previous heat pump systems is the comparative long warm-up time. As discussed earlier, the dryer vent is closed during the warm-up period. As testing with the heat pump validation unit progressed, it was learned that the drum pressure was close to 0" WC when the exhaust vent is closed. In standard dryers, the drum pressure is typically slightly negative. This slight negative pressure helps to prevent lint migration through the seals of the drum. Since the closed loop portion of the heat pump

dryer cycle was operating around 0" WC drum pressure, there is the risk of lint migration through the seals. However, the fabric is wet during this time period and not yet prone to linting. To limit the lint migration through the drum seals, it is key to minimize this warm-up period.

This limiting effect was achieved by integrating a boost heater into the process airstream. This boost heater serves to increase the inlet temperature into the drum and allows the dryer to complete the warm up phase in less than half the time as compared to a heat pump only operation.

With many of the overall system parameters defined, work began on refining the airflow system. As detailed earlier, maximum airflow rates are desired in order to maximize heat output from the heat pump. 250 cfm was defined as a target airflow level. However, this airflow presents problems with fabric plastering, as detailed earlier, and system pressure drop. Figure 1-7 shows the measured pressure drops in the airflow prototype dryer system for varying flow rates.

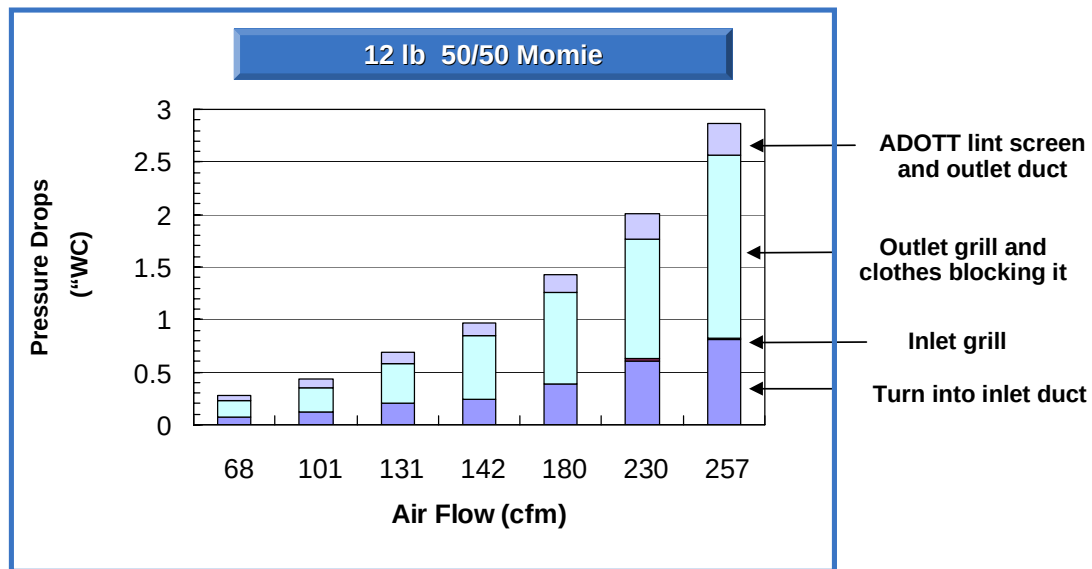


Figure 1-7: Pressure Drop vs. Flow Rate on Airflow Prototype

Since the airflow prototype was a representation of a heat pump system, actual pressure drops are likely to be different for the heat pump validation unit, though the trends would be similar. As the figure shows, pressure drops approaching 3" WC are realized at flows around 250 cfm. In order to achieve these flow rates at these pressure drops, the blower system becomes prohibitively expensive and oversized. To counter this, various means to reduce the system pressure drop were investigated.

As shown in Figure 1-7, the outlet grill and the clothes blocking it is the most significant component in the system pressure drop. Significant testing and flow modeling was done to identify means to reduce this pressure drop without adversely affecting the dry process. What was identified was an approach where a second outlet grill is used.

Figure 1-8 shows the effect of adding this second outlet grill. This test data is from the heat pump validation unit and shows over a 50% reduction in system pressure drop.

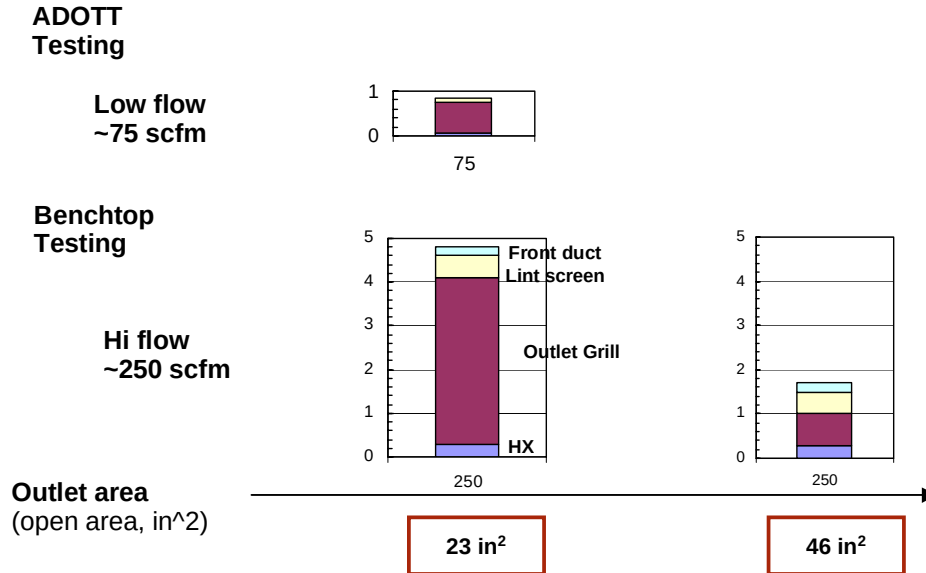


Figure 1-8: Pressure Drop Effect From Adding a Second Outlet Grill

The added outlet grill had the desired effect on system pressure drop. However, the challenge lay in designing the necessary ducting system to accommodate this second exit. The air leaving this new outlet had to be brought to the front of the dryer cabinet in order to pass through the lint screen and proceed into the heat pump region.

This configuration added some complexity to an already difficult issue: lint management. As discussed earlier, lint management in a heat pump dryer design is of paramount importance since lint migration beyond the screen can cause issues with the heat exchangers. Lint screens of varying geometry and mesh designs were tested on our heat pump validation unit. The chosen design was one that employed a lint screen that was 1-1/2 times larger that utilized a much finer mesh (85 mesh count per inch as compared to 23 in the standard screen). Testing on the demonstration unit showed this design to be adept at preventing excessive lint migration into the heat exchanger region. However, more extensive life cycle testing is needed to see the long-term effects of linting in this design.

1.4. Sensors and Controls Approach

With the design specification in place and a completed verification unit ready for in-depth testing, the last key step was to identify the necessary sensors and controls to operate the heat pump dryer to its fullest extent. The major sensing system that needed to be developed was one that could identify when to modulate the heat input. Since the dryer design integrated a boost heater element into the process flow, when and how to cycle the element was the first sensing and control need. Through testing it was determined that the element could be cycled using a temperature measurement in the

rear duct of the dryer before the air enters the drum. This temperature is used as part of the dryer control to modulate the heating element on and off as needed. This same RTD input is also used to identify the point in the cycle when the warm-up is complete and the vent can be opened to the outside.

Since the boost element's main function is to speed up the warm-up period associated with the heat pump system, its usefulness tends to diminish after this warmup has occurred. Once the fabric starts to dry and the constant rate drying period has ended, the element is no longer needed. During the development and testing process it became clear that a signal in addition to rear duct temperature would be needed to identify this point. Various approaches were investigated including humidity sensors, moisture conductivity strips and various additional RTD locations. After rigorous testing, the most robust and, in many ways, the simplest, approach was found to be a second RTD in the front duct, upstream from the heat exchangers. It was determined that the temperature difference between the front and rear duct RTDs provided enough information not only to decide when to cease use of the boost element, but also when to end the dry cycle and shut down the compressor. This approach was initially tested with the following three loads:

- 1) Extra large load as represented by 12lbs (dry) of towels;
- 2) Medium or normal loads as represented by 7lbs (dry) of cotton cloth;
- 3) Delicate loads as represented by 3 lbs (dry) of lingerie and nightgowns;

Testing with these three loads showed the Delta RTD approach to be very reliable and repeatable. This approach was used for the dryer algorithm for all of the testing results presented in the next section.

1.5. Product Testing

All of the initial performance testing was performed at TIAX. Much of the final performance testing on the demonstration unit was done at Whirlpool's own testing labs. Clothing loads were selected to represent a range of loads that were likely to be used by the consumer.

The key parameters measured were total drying time, which included a cool down at the end of the cycle, total energy consumption, fabric temperature (as measured with temperature strips attached to individual pieces of clothing) and final moisture content. A load was determined to be dry if it met Whirlpool's specification for remaining moisture content (RMC). In addition to the experiment measurement, a final qualitative assessment was made by Whirlpool's test technician.

The following tables show some of the representative results. Market best refers to the electric unit currently available on the market that was assessed by Whirlpool to be the best for that load. Heat pump refers to the heat pump dryer that has been described in this paper. Energy is the total energy consumption in KWh for the total dry cycle for the given load. Fabric temperature was determined by averaging the readings from 8 to

10 temperature strips attached directly to individual pieces of clothing in the load. In all cases, RMC was within allowable specifications.

Multiple tests were performed for each load according to Whirlpool's internal test specification. Initial moisture content for all loads was tightly controlled in order to make fair and consistent test comparisons between clothes dryers.

<i>Delicate Load</i>			
Dryer	Time, mins	Energy	Fabric Temp.
Market Best	22.2	0.74	120
Heat Pump	14.4	0.44	110
Gain	35%	41%	10°F

Medium, 7lb cotton load			
Dryer	Time, mins	Energy	Fabric Temp.
Market Best	39	2.90	185
Heat Pump	42	1.97	155
Gain	-8%	31%	30°F

Large, 15lb Towel Load			
Dryer	Time, mins	Energy	Fabric Temp.
Market Best	78	6.28	190
Heat Pump	78	3.52	155
Gain	-	44%	35°F

As the tables show, the heat pump dryer delivered dry times that were similar or faster than the market best for all loads while delivering energy savings between 30-50% and dramatically lower fabric temperatures.

1.6. Conclusion

Consumer feedback work conducted on this program indicates a willingness on the part of US consumers to consider the purchase of a heat pump dryer, provided key performance attributes of fast dry times and enhanced fabric care are achieved. Through the application of a rigorous product development process, TIAX, with guidance and assistance from Whirlpool Corporation, developed a heat pump clothes dryer that demonstrated this desired superior performance. Using the Whirlpool ADOTT dryer with pedestal as the design platform from which to develop the heat pump unit, multiple iterations were designed, constructed and tested in order to develop the final refined design. The final configuration was demonstrated to achieve the significant energy savings and fabric care typically associated with heat pump systems along with significant reductions in total dry cycle times. This is especially true when the demonstrated performance is compared to existing European heat pump dryers.

This dramatic improvement in performance was achieved by taking a decidedly different approach to the heat pump system in order to maximize the capacity. By maximizing the output capacity and temperature from the heat pump, the heat pump

dryer was able to deliver 30-50% energy savings and dramatically lower cloth temperatures in total dry times for varying types of clothing loads that were similar or faster times than the market-best standard electric dryer. This level of performance is right in line with what consumers were saying they needed from a high efficiency dryer.

The final configuration and all the detailed design decisions that led to this version have been transferred to Whirlpool Corporation and are proceeding through their internal processes toward commercialization. The final step in this transfer process is summarized in Appendix 1, the Heat Pump Dryer Technical Design Preview that was delivered to Whirlpool in April, 2003.

VOLUME 2 – Development of a Modulating Gas Dryer

2.0 Introduction

At the start of this program, extensive consumer feedback focus group studies were performed in the Boston, Chicago and San Jose areas in order to better understand consumer wants and desires with respect to laundry. The primary objective of this consumer feedback process was to quantify the relative importance of energy use, time to dry and purchase cost to consumers of gas and electric clothes dryers. Specifically, the following areas were explored:

- Consumer sensitivity to energy issues and perceived value of energy savings;
- Consumer response to different descriptions of energy opportunities (i.e. response to potential approaches to marketing energy savings);
- Consumer sensitivity to dry time and desired relationship between dry time and wash time;
- Impact of key dryer features and functionality on the likelihood of purchase.

It was determined that current owners of gas clothes dryers were willing to pay significantly more to achieve energy savings, however, cost sensitivity varied by location. In addition, the following results were gathered from these focus group activities:

- Most consumers needed a minimum of 15-25% energy savings to affect their purchase decision of a clothes dryer;
- The top three purchase criteria for clothes dryers were listed as reliability, features and functions, and price;
- Consumer interest in energy efficiency is not tied to payback but rather to a desire to do what is environmentally sound;
- Waiting for the dryer to finish its cycle was considered to be one of the most time consuming laundry tasks;
- A dry time that truly equals the wash time was of paramount interest and value to the participants, however, faster than the wash time had no extra value;
- Participants withheld as much as 50% of their clothes from the dryer from fear of cloth damage, mainly due to excessive heat.

With this market information as a starting point, work began on developing a modulating gas dryer that could meet these market needs.

2.1. Developing a Dryer to Meet The Market Needs

In order to address the consumer needs and deliver an energy efficient gas dryer, a new approach was needed. Most gas dryers on the market today operate with a single burner at a fixed input rate and a fixed airflow rate (varying only in response to load size and venting configurations, which create the system pressure drop). The burner typically operates in an on/off mode as determined by the cycle chosen and the temperature of the

exhaust flow. Many dryers integrate a type of moisture sensor, the most common being conductivity strips, to assist in identifying when to terminate a cycle. These strips serve to measure gross detection of load wetness and typically do not provide much indication of how wet or how dry the fabric is. In order to maximize energy savings and minimize total dry times, it is imperative to have a true end-of-cycle indicator.

Gas dryers are best positioned to deliver reduced drying times. This is possible because they do not have the same upper power limit that is associated with the line cord power to an electric dryer. However, implementing a time saving system into a gas dryer is not as simple as merely increasing the input rate. Without properly balancing the gas input and airflow rates, excessive drum inlet temperatures arise resulting in the risk of clothing damage. This is especially true as the clothes begin to dry. The key is to match (or modulate) the heat input rate to the moisture level of the load. In order to achieve this, the following criteria have to be met:

- it must be determined that the clothes are, in fact, wet (and ideally, how wet);
- consistent airflow must be delivered to control inlet temperature; and
- installation variations must be compensated for.

A clothes drying simulation tool was developed to assist in the product development activities. This tool modeled the heat transfer between the inlet air of a clothes dryer's drum and the clothing load in order to make estimations of evaporation rates, clothing temperatures and projected dry times. Output from this model was used to assist in the hardware development effort.

The simulation model showed that the key to developing an effective modulating gas dryer lies in being able to:

- Define the necessary input rates to handle the range of clothing loads the dryer will encounter;
- Deliver the proper airflow for the varying input rates across a range of vent restrictions;
- Have the necessary sensors and controls in the dryer to detect the onset of the falling rate drying period, reduce the input rate as the clothes are approaching dry and properly detect the end of the overall cycle.

2.2. Defining the necessary input rates

When the clothes are wet, the input heat can be maximized. The definition of a maximum input rate for a modulating gas dryer takes into account several different aspects including:

- Input from consumer feedback studies (dry times only need to match wash times)
- Certification issues such as combustion performance, surface temperatures, etc.
- Space considerations (this design had to fit into a standard dryer cabinet space)
- Performance tradeoffs (dry time, fabric temperature, noise, energy consumption)

The consumer feedback study had clearly shown willingness on the part of consumers to pay more for a dryer that could dry any load of clothes equal to wash times. In standard dryers, this target is already met for many smaller and medium clothing loads, but it is missed with many larger full size loads. A 15 lb (dry) cotton towel load was chosen as the metric by which dry time was to be measured. Wash times in a standard heavy-duty washing machine cycle for this type of load was defined as 48 minutes. The standard gas dryer dried this load in 70 minutes, so a 35% time reduction was necessary in order for the dry time to match the wash time. With this time limit in place, work began on developing the maximum input rate and the modulation steps for this gas dryer.

The clothes drying simulation tool was used extensively to gain an understanding of how input rate and modulation effected dry times, fabric temperatures and energy efficiency. In addition, an initial laboratory prototype was used for the early testing to experimentally determine the effects of modulation. Based on this modeling and the initial test results from the first prototype, 40,000 Btu/hr was defined as the maximum input rate for this dryer.

This input rate presents no issues when the clothing load is wet and able to absorb the heat. As the clothes begin to dry, this input rate is no longer desired. At this input rate, as the clothes begin to dry, excessive airflow rates would be needed to keep fabric temperatures at reasonable levels. In addition, other cycles, such as ultra delicate and delicate cycles, require significantly lower fabric temperatures than a heavy-duty load, therefore, other input rates are needed. In determining the proper modulation steps needed for this dryer, the following four key metrics were used:

- Drying time targets (must equal wash time)
- Fabric temperature targets (fabric care, increase % of fabrics trusted to a dryer)
- Efficiency targets (15% minimum savings)
- Cost and complexity issues.

Again, the clothes drying simulation tool was used as a starting point to understand how different input rates might effect dry time, fabric temperatures and energy efficiency. After running extensive simulations, the following classes of input rates were defined:

- 1) High - as discussed earlier at a maximum of 40,000 Btu/hr;
- 2) Medium - a rate similar to today's standard gas dryers;
- 3) Low - a rate less than half of today's standard dryer

With these general ranges in mind, work began on identifying how to design the hardware to deliver these input rate ranges. This process started with the high input rate of approximately 40,000 Btu/hr. Most standard dryers today use inshot style burners to deliver the heat to the drum. At 40,000 Btu/hr, using a single inshot burner becomes very difficult due to flame length and the risk of excessive metal temperatures. This led to a design approach that uses two inshot burners firing into a combustion chamber that is larger than normal. This is shown in Figure 2-1 below.

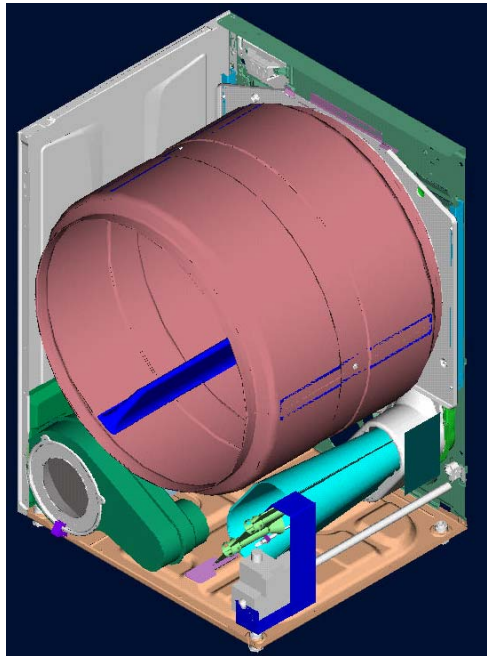


Figure 2-1: Physical Layout of Modulating Gas Dryer

These two inshot burners are configured in such a way that they fire into an oval shaped combustion funnel before turning up the rear duct and then entering the drum. Airflow is induced by a blower (shown in green) located downstream of the dryer drum. Combustion and performance testing on the validation unit confirmed this design.

2.3. Delivering the proper airflow to allow for gas modulation and installation venting considerations

On high, the modulating dryer is operating at a maximum input rate that is nearly twice the rate of a standard dryer. Flow considerations in the combustion chamber and the rear duct is critical to ensure proper burner performance and to prevent excessive inlet grill air temperatures. Before the validation unit was built, extensive CFD flow modeling was performed with the two-burner design. The key aspects investigated were:

- 1) Methods to distribute the air evenly through both burners;
- 2) Rear duct flow modeling to promote good mixing of hot and cool flow regions; and
- 3) Drum inlet configuration to optimize flow mixing with the tumbling clothes.

All of this was done with the constraints of developing a ducting system that could be accommodated with little modification to existing plant tooling. Figures 2-2 through 2-4 show some of the flow modeling results. Figure 2-2 shows the effect of increasing the funnel to rear duct collar length on flow uniformity. Flow was modeled through each burner. As the collar length is increased, the ratio of the two burner flows approaches 1. While dryers typically have more than sufficient airflow for combustion purposes, obtaining even airflow through each burner region is still desirable. Figure 2-3 shows the effect of collar to rear duct geometry on flow uniformity in the rear duct. This transition was modeled as a 90-degree bend, a 45-degree bend and a gentle radius. As the figures show, both the gentle radius and the 45-degree bend represent a large improvement over a 90-degree turn. Figure 2-4 shows the flow entering the drum. Different configurations were modeled in order to develop an approach that optimized flow in the drum.

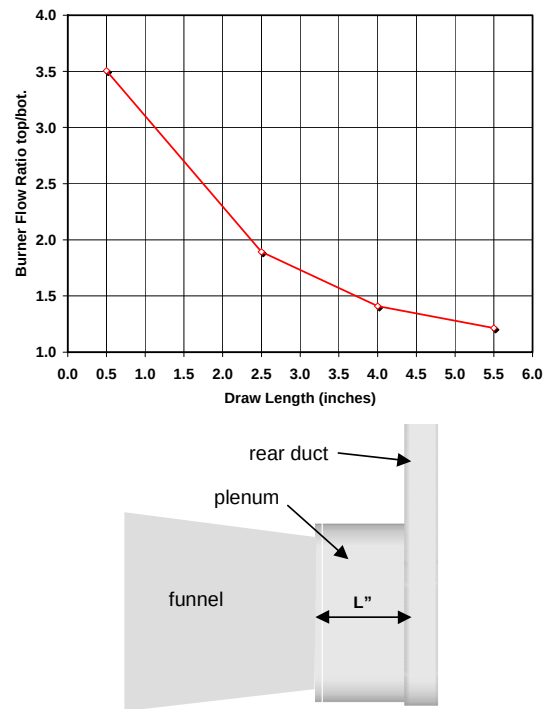


Figure 2-2: . Effect of Draw Length on Flow Uniformity

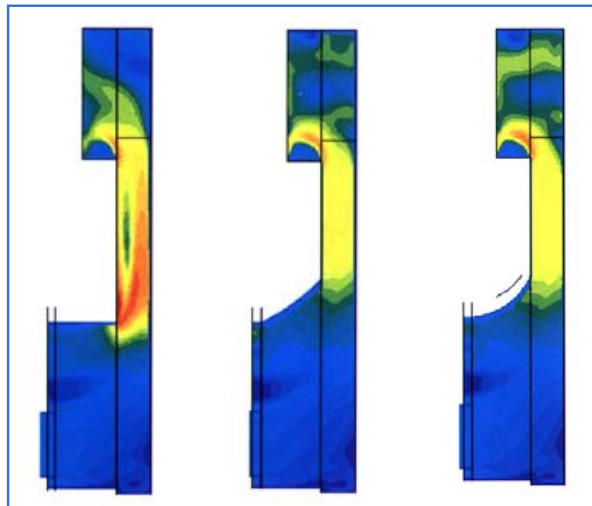


Figure 2-3: Effect of Collar to Duct Inlet Geometry on Rear Duct Flow

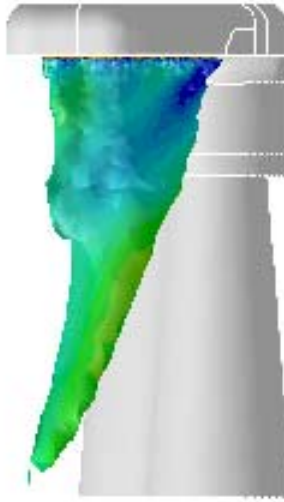


Figure 2-4: Modeled Flow Out of The Rear Duct into the Dryer's Drum

The CFD flow analysis, combined with extensive discussions with Whirlpool's tooling engineers, led to a new funnel/collar/rear duct design that could deliver improved airflow and be producible with minimal modifications to existing tooling.

Since this new dryer was going to have a minimum of three input rates, the single airflow approach used on standard dryers would not be sufficient. In addition, flow control is of the utmost importance since the dryer is intended to maximize energy efficiency and limit fabric temperatures. To deliver the varying airflow rates needed, a variable speed blower approach was selected and implemented on the validation unit.

With this information, a verification unit was constructed and used as the basis for performance testing. The verification unit was built with two inshot burners firing into a new funnel/collar rear duct arrangement married to an existing dryer drum. Modifications were made to the exhaust ducting in order to accommodate the variable speed blower and the necessary sensors and controls needed to improve performance.

The verification unit served as the tool to refine the input rates and to investigate flow considerations. Initial unit testing centered on defining in practice the best modulation steps to integrate into the dryer and how to deliver and control these rates. This product definition step was overlaid with a matrix of test clothing loads that were intended to represent a range of test conditions, namely

- 1) Extra large load as represented by 15lbs (dry) of towels;
- 2) Medium or normal loads as represented by 7lbs (dry) of cotton cloth;
- 3) Delicate loads as represented by 3 lbs. (dry) of lingerie and nightgowns;

These three loads served as the initial basis for refining the dryer design. As mentioned earlier, the towel load was chosen as a maximum load in which time savings was the most important parameter. The 7-lb. cotton load was chosen as a more typical load

where demonstrating energy improvement would hold the most value. The delicate load was chosen as a measurement tool for demonstrating the benefits of modulation to fabric care, as measured by maximum fabric temperature during the dry cycle.

With the testing completed, the following general cycles were identified:

- Heavy Duty
- Normal
- Delicate

As detailed earlier, it is of critical importance that the airflow in the dryer be consistent in order for the performance to be maximized. This was easy to achieve in the lab, but in the field, variations in installations represent a significant hurdle to ensuring consistent airflow. Figure 2-5 shows the effect installation variation has on airflow in the dryer. The figure shows the measured airflow for a similar dryer over a range of pressure drops that are typical of household installations. Notice that the flow rate drops nearly in half over this range of installations. In practice, this means that the dryers operating at the right portion of the curve tend to short-cycle due to the low flow rate achieving the maximum allowable exhaust temperature faster than if the flow rate were as intended. The result is higher drum inlet temperature, higher fabric temperatures and longer dry times due to the short-cycling. In a modulating dryer, this effect is magnified by the existence of the higher input rate and the tuned airflow rate to maximum energy efficiency. This confirms the critical importance of flow control.

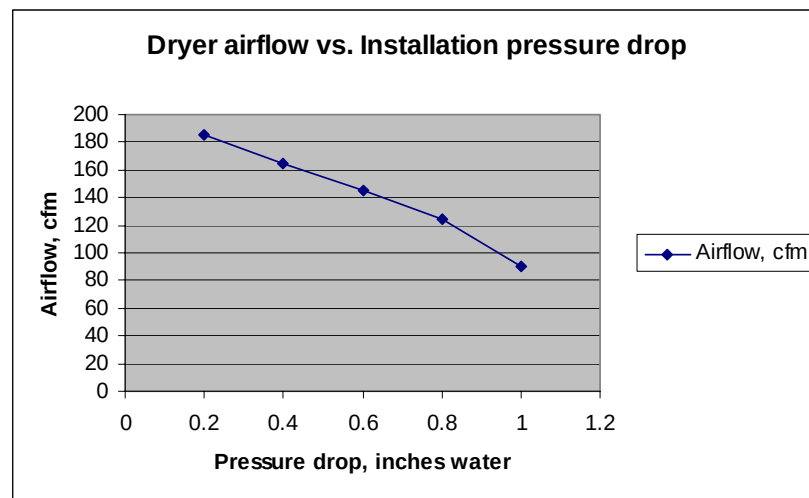


Figure 2-5: Effect of Installation Variations on Flow Rate Through a Dryer

Since a variable speed blower was already selected for implementation in this design in order to deliver multiple airflow rates to match the modulating input rate, the ability to adjust the airflow was present. The key was to develop a system that was able to detect installation variations and adjust the flow accordingly. Numerous options were investigated. In the end, what was selected was a system that uses a pressure switch in the exhaust flow stream from the dryer. At the beginning of a dry cycle, the blower speed is increased until the pressure switch is tripped. The speed at which the blower

was able to trip the switch provides the necessary indication of what level of installation restriction exists. The graph below illustrates how this system works. As the pressure drop increases with varying installation for a given flow rate, the blower speed needed to develop this flow rate increases. The speed at which the switch trips then serves as a lookup table for where the other flow rates in the cycle need to operate.

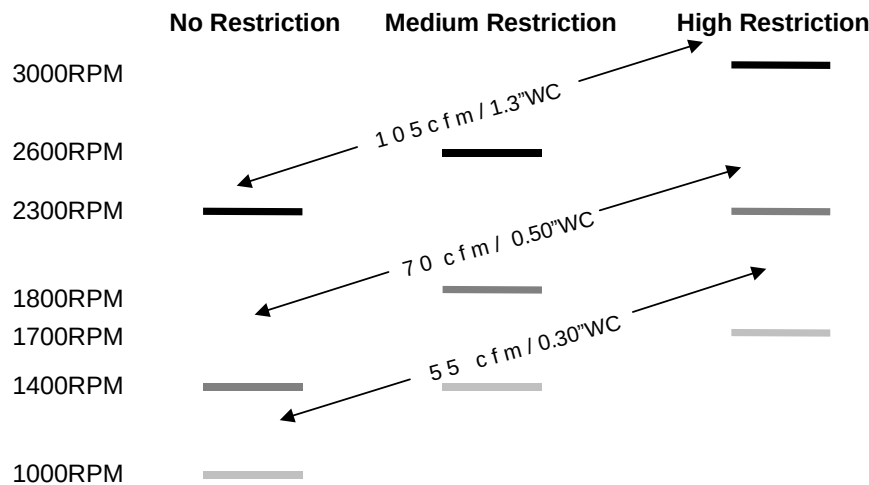


Figure 2-6: Pressure Switch Approach to Adjust Flow Rate for Varying Installation Restrictions

This flow control approach was tested extensively on the verification and demonstration units and was shown to be robust over a wide range of installation conditions. This approach allows the rest of the dryer's sensors and controls to operate as intended and serves to maximize drying efficiency while minimizing dry times. With this system in place, extensive product testing was undertaken to demonstrate improved performance.

2.4. Sensors and Controls Approach

The conductivity strips used in most dryers provide an indication that the clothes are wet, however, these typically do not indicate the degree of wetness. To augment the output from the conductivity strips, a second signal is needed. In the course of the product development on this product, two additional signals were analyzed and refined:

- Rate of exhaust temperature rise
- Humidity sensing in the exhaust

With a known flow rate, the temperature in the exhaust gives an indication of the amount of moisture inside the drum. This signal is used to determine when to perform the first and second modulation steps. This temperature, combined with a signal from a humidity sensor in the exhaust, is then used to determine the end of the cycle.

2.5. Product Testing

Initial evaluation testing was done at TIAX. Much of the final performance testing was done at Whirlpool's own testing labs. Clothing loads were selected to represent a range of loads that were likely to be used by the end user.

The key parameters measured were total drying time, which included a cool down at the end of the cycle, total energy consumption, fabric temperature (as measured with temperature strips attached to individual pieces of clothing) and final moisture content. A load was determined to be dry if it met Whirlpool's specification for remaining moisture content (RMC). In addition to the experimental measurement, Whirlpool's test technician made a final qualitative assessment.

The following tables show some of the representative results. Market best refers to the unit currently available on the market that was assessed by Whirlpool to be the best on the market for that load. Mod. Gas refers to the modulating gas dryer operating with three input rates. Energy is the volume of natural gas consumed during the dryer process plus an adjustment for electrical consumption. Fabric temperature was determined by averaging the readings from 8 to 10 temperature strips attached directly to individual pieces of clothing in the load. In all cases, RMC was within allowable specification.

Multiple tests were performed for each load according to Whirlpool's internal test specification. Initial moisture content for all loads was tightly controlled in order to make fair and consistent test comparisons between clothes dyers.

<i>Delicate Load</i>			
Dryer	Time, mins	Energy	Fabric Temp.
Market Best	15	2.2	113
Mod. Gas	12	1.8	109
Gain	20%	18%	-4°F

<i>Medium, 7lb cotton load</i>			
Dryer	Time, mins	Energy	Fabric Temp.
Market Best	30	9.7	172
Mod. Gas	18	7.5	148
Gain	40%	23%	-24°F

<i>Large, 15lb Towel Load</i>			
Dryer	Time, mins	Energy	Fabric Temp.
Market Best	64	24	172
Mod. Gas	47	21	168
Gain	28%	13%	-4°F

As the tables show, the modulating gas dryer outperformed the market best for all load sizes. Energy consumption was reduced by 13-23% as compared to the market best. Time improvements ranged from 20-40% over the market best. And finally, average fabric temperatures were lower than the market best for all loads, providing an indication of fabric care associated with this approach.

2.6. Conclusion

Consumer feedback work conducted on this program indicated that consumers were very responsive to a gas dryer which could save significant amounts of time for the overall drying cycle, provided there was no adverse effect on energy efficiency or cloth temperatures. Over the course of the program, a scheme for modulating the gas flow in a gas dryer was developed and shown to deliver the performance attributes desired by the consumer. Integrating Computational Fluids Dynamics flow modeling, a proprietary dryer process simulation model and extensive market and manufacturing experience, a modulating gas dryer prototype was built, refined and demonstrated to deliver superior performance.

Extensive product testing of this modulating gas design showed significant improvements in dry time and energy consumption in an approach that limits maximum fabric temperature. Energy savings up to 25% were demonstrated across a range of loads. For the extra large loads where time savings are most significant, time savings up to 35% were demonstrated. Modulation was also shown to dramatically improve fabric care through lower cloth temperatures. By reducing or modulating the gas input rate as the clothing load was drying, reductions in cloth temperatures up to 25oF were realized. Added to this performance improvement was an approach that allowed for more consistent operation across a range of venting restrictions found in typical installations. This more robust performance further enhanced the virtues of the final design.

The final configuration and all the detailed design decisions that led to this final version of the modulating gas dryer have been transferred to Whirlpool Corporation and are proceeding through their internal processes toward commercialization. The final step in this transfer process is summarized in Appendix 2, the Modulating Gas Dryer Technical Design Preview which was delivered to Whirlpool in February, 2003.