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GAS-FIRED HEATERS FOR PLASTICS PROCESSING

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GAS RESEARCH INSTITUTE
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GAS-FIRED HEATERS FOR
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FINAL REPORT
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This report describes the design, fabrication, and testing of a novel natural gas fired radiant heating system suitable for heating and curing plastic film and sheet. Prior to this, gas-fired systems have not been used widely in this industry because they fail to meet process requirements and provide necessary cost incentives. Recent developments have produced gas-fired radiant tubes that can provide heat flux levels and thermal efficiencies necessary to enter the plastics processing market. These units are not useful for this application unless a means is introduced that efficiently and uniformly transfers radiant tube emission to target surfaces. It is proposed that advanced reflector systems can provide the means needed. The concept tested during this study uses an involute specular reflector to efficiently couple gas-fired radiant tube emission to a target surface. Performance testing shows that this concept will lead to gas-fired heating systems that are nominally 45% less costly to operate than 90% efficient electric units and will be capable of providing target surface heat flux levels and target surface heat flux variations that are compatible with requirements germane to the plastics processing industry.

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Objective

The overall objective was to experimentally demonstrate the potential of a novel natural gas fired radiant heating system concept for plastics processing. The sequential objectives were to: identify performance goals the system must achieve to effectively penetrate plastics processing markets, markets that have been dominated by electric systems; design and build a bench-top system that would provide performance results that could be compared with identified performance goals; and construct a critical assessment of the potential of the proposed concept based on achieved versus identified performance goals.

Technical Perspective

Electric units dominate the plastics heating system market. Alternately, 10,000 gas-fired units could be used, increasing gas consumption by 5-10 Bcf/year. Heating sheets and films via infrared ovens is the most suitable application for gas-fired systems. Gas-fired ovens are not used because they fail to meet process requirements and to provide necessary cost incentives. Broad acceptance of gas-fired systems will require higher efficiencies, improved heat flux uniformity, and acceptable temperature control and response. Gas-fired radiant tubes can deliver the efficiency, temperature control, and response needed. Heat flux uniformity can be achieved by coupling radiant tube emission to target surfaces using reflectors. This concept was tested during this study.

Results

The tested gas-fired heating system met or exceeded almost all goals. Target goals and measured performance are summarized below.

	Goal	Measured
• Overall thermal efficiency:	>50%	53-56%
• Surface heat flux level:	4-6 W/cm^2	3-5 W/cm^2
• Surface heat flux uniformity:	Within ±15%	±15% (max)

Measured efficiencies decreased slightly with increasing firing rate and, as expected, measured surface heat flux levels increased. The measured efficiencies imply that heating systems based on this concept will be 44-47% less costly to operate than an electric unit with 90% efficiency when both systems deliver the same power to a target surface. This assumes, on a per unit energy basis, that the cost of electricity is three times the cost of natural gas. Although the surface heat flux uniformity goal was achieved, future systems should strive to achieve target heat flux variations within ±5%. A value of ±15% was adopted for this study because an unoptimized reflector system was tested. Target heat flux variations normal to the radiant tube fell within the ±15% tolerance. Due to radiant tube axial temperature gradients, target heat flux variations parallel to the radiant tube were found to be ±20%. By counter-staggering radiant tubes in heating banks, variations within ±10% appear feasible using the tested reflector system. No issues were identified that might prevent this approach from achieving the ±5% tolerance.

Technical Approach

Recent developments have lead to gas-fired radiant tubes that can provide heat flux levels, thermal efficiencies, and target surface coverage necessary for plastics heating processes. They are not useful for this application, however, unless a means is integrated into the heating system that efficiently and uniformly transfers radiant tube emission to target surfaces. Textron Defense Systems (TDS) proposed that a reflector system could provide the means needed. The synergism of state-of-the-art gas-fired radiant tube and advanced reflector technologies forms the basis of the concept proposed by TDS. This approach shows good promise as a heating system concept that will meet plastics processing requirements and provide substantial cost benefits to the plastics industry. This concept was explored during this study by building and testing a bench-top test rig. The basic configuration of the test rig was a parallel tube heat exchanger. The upper tube was a gas-fired radiant tube burner. The lower tube was a water cooled receiver tube containing a heat flux gauge. The radiant tube emission was imaged onto the receiver tube via an involute shaped specular reflecting cavity that completely enclosed both tubes. By traversing/rotating the receiver tube in the reflector cavity, the heat flux gauge provided spatial heat flux distributions over the irradiated surface of the receiver tube. By monitoring the fuel flow rate into the radiant tube burner and by making calorimetric measurements of the radiant power collected by the receiver tube, overall thermal efficiency was determined. Although proximity infrared heaters are the most appropriate for plastics processing, the parallel tube configuration was studied because a closed system is preferred for making accurate system energy balances. Axial and circumferential heat flux profiles, as well as thermal efficiency measurements were made at several firing rates. The potential of this approach was assessed by comparing these measurements with performance goals based on requirements germane to the plastics processing industry.

Project Implications

This research explored the technical feasibility of using a gas-fired radiant heat source and specular reflector to achieve uniform, controlled heating of a load. The results show that heat flux levels commonly used in plastics forming processes can be reached, and that a system based on this concept would have relatively low operating coats. A ceramic radiant tube burner was used as the heat source, but it was shown that improvements in the temperature uniformity along the length of the burner would be needed to meet the requirements of the plastics industry. GRI's Industrial Utilization Department will consider the results of this Exploratory Research Project before initiating a project in 1993 to develop a gas-fired heater for the plastics industry.

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1.0 INTRODUCTION

1.1 BACKGROUND

1.1.1 Motivation and Requirements

A broad spectrum of heating and curing systems are used for manufacturing plastic stock and end-products. Plastic stock refers to bulk forms used for manufacturing finished parts and those that can be used directly, and encompasses: plastic films, sheets, laminates, and extrusions such as tubing. Plastic end-products refers to finished parts ready for packaging and sale or those ready to be introduced into an assembly line for producing integrated units. Plastic end-products are abundant and one needs only to quickly survey his/her home, automobile, office, plant, etc. to realize their prevalence. Heating systems are essential for producing plastic stock and end-products of high quality with desired properties and are used for: thermosetting, thermoforming, and laminating plastic sheet and film; heating screw barrels of injection molding and extrusion machines; heating liquids circulated through calendar rolls, molds, presses, and reactors; heating cartridge, band, and strip molds; preheating composites prior to molding; and drying plastic feedstock.

Given the energy intensiveness of the heating processes required for plastics processing and the extensive and rapidly escalating use of plastics products in the industrial, commercial, and domestic sectors, the plastics industry offers energy and heating systems suppliers very promising markets. Although gas-fired ovens and heaters are used currently for some plastics heating applications, electric power suppliers and electric heating system manufacturers dominate this market[1]. In order to explore potential avenues for increasing the natural gas industry's share in this market, Hagler, Bailly, and Company[2] (HBC) conducted a study funded by Gas Research Institute that delineates the competitive position of natural gas based heating systems relative to electrically based ones for plastic processing applications. The key results of this study are summarized below, followed by Textron Defense Systems' (TDS) response to the implications of these findings. The TDS response formed the conceptual basis of the gas-fired heating system approach explored in the present study. Within the presentation of TDS's response, extensions are made which suggest that the proposed concept also shows promise as a basis for heating systems for plastics processes beyond those targeted by HBC.

The key findings given by HBC include: specific plastics heating processes where natural gas-fired systems could provide significant cost benefits to plastics manufacturers and open up substantial markets for natural gas and gas-fired heating system suppliers; the most advantageous heater configurations for these processes; and the technological requirements that gas-fired heating systems must meet to enter these markets. HBC focussed their study on opportunities that may exist for gas-fired heating systems in the miscellaneous plastics products industry for curing and heating plastic films and sheets. HBC's report reveals that this market is presently serviced almost entirely by electric power and equipment suppliers (although some gas-fired systems are used in this market); it represents approximately 20 percent of all plastics production; 10,000 advanced gas-fired heating systems could be used in this market if these units met process and cost requirements; and 5 to 10 billion cubic feet per year of new natural gas sales could be realized if advanced gas-fired heating systems were accepted by this segment of the plastics manufacturing industry. These findings suggest that development of natural gas heating systems which meet this market's process requirements and provide cost advantages over electric systems should produce substantial returns to natural gas and gas-fired heating system suppliers.

As discussed by HBC, many types of processes are used for manufacturing plastic films and sheets, namely: film laminating, reinforced plastics laminating, extrusion, solvent and acrylic casting, and transfer coating. Extrusion-based processes appear to be the most favored approach for producing films and sheets. All of these processes require heating systems either for curing, conditioning, or forming. HBC's report also explains that the type of heating system used for a particular film/sheet manufacturing process is determined by several factors, namely: critical process variables (e.g., resin used, curing agent, curing temperature, curing time or heating cycle constraints, and temperature uniformity and control); system operating and capital costs; and secondary process compatibility constraints (i.e., solvent vapors and open flame heating systems are not compatible).

Based on production line considerations, tunnel-oven heating systems are the most appropriate for film and sheet manufacturing processes. Two distinctly different types of ovens are commonly used, namely: convection and infrared ovens. Both of these ovens can use natural gas or electricity as a source of heat. Relative to infrared ovens, convection ovens have inherent disadvantages, the most prevalent being low efficiency, long cycle times, and bulk size, which is true regardless of the heat source used (i.e., electricity or natural gas). By virtue of their higher efficiency, broad operating range, faster response, and reduced floor space requirements, infrared ovens offer the plastics manufacturer the greatest performance/cost benefit. For these reasons, development of improved convection-based heating system concepts was not adopted for this exploratory study, and therefore will not receive further attention in this discussion.

Given the properties of the raw materials used to produce films and sheets, heating/curing temperatures in the range 370-480 K (200-400 F), controlled to within ±3 C (±5 F), are required[1] on and in the film and sheet being processed. HBC presents a rule-of-thumb which translates these temperature requirements into surface radiant flux requirements for infrared heating systems, i.e., radiant heat flux densities of nominally 4 W/cm^2 (25 W/in^2) are ideal for heating plastic sheet. HBC also stress that this rule-of-thumb flux density may vary depending on the radiant source emitter and the application. These requirements have been instrumental as guidelines for tailoring the performance of the novel gas-fired radiant heating system developed during this exploratory study.

Regarding the competitive position of gas-fired ovens for plastic film and sheet processing, HBC states that gas-fired units are cost-competitive with electric units, but performance issues continue to orient this industry towards electric heating systems. The issues hindering broader acceptance of gas-fired heating systems are temperature control, response time, and efficiency. They also state that open flame gas heaters are not appropriate for solvent extraction processes where combustible vapors are present. HBC conclude their report by stating that improvements in gas technologies which address these issues would improve the competitive position of gas-fired heating systems and would contribute, therefore, to increased gas consumption in the plastics industry.

To summarize, the following key information has been derived from the study by HBC. First, the plastic film and sheet manufacturing industry represents a significant new market for the natural gas industry. Second, infrared heating ovens are the most advantageous configuration for processing films and sheets. Third, infrared heating system requirements (flux density, temperatures, etc.) appear achievable using natural gas technologies. Fourth and last, developmental efforts seeking to enhance the competitive position of natural gas based systems in this segment of the plastics industry must improve the temperature control and response time performance relative to existing gas-fired systems, as well as producing a system that has greater cost benefits by being more efficient.

1.1.2 Increasing The Competitive Edge of the Natural Gas Industry

Based on the key information derived from HBC's study and other sources, TDS formulated a gas-fired infrared heating system concept which has the potential for overcoming the obstacles hindering utilization of natural gas based heating systems in the plastics industry. This report describes the design details and results of an exploratory study involving a bench-top, prototype system based on TDS's novel concept. A brief overview of this concept follows with comments describing the manner in which it addresses the technological requirements and challenges outlined above (i.e., temperature control, response time, efficiency, and process compatibility).

Since most markets are driven by performance/cost-benefit compromises, advanced gas-fired plastics heating systems must provide the plastics industry with cost-benefit incentives sufficient to motivate their conversion to natural gas systems. Since heating systems are energy intensive, achieving these incentives implies that advanced heating systems must attain higher thermal efficiencies. Assuming a 3:1 ratio for the cost of electricity to natural gas (on a per unit energy basis), the operating fuel-costs for a 30% efficient gas-fired heating system would be comparable to those for a 90% efficient electric unit. The 30% thermal efficiency point, therefore, represents the break-even point where no advantage exists for converting to gas-fired systems. If the efficiency of gas-fired systems could be elevated to 50%, however, the plastics industry would realize a 40% reduction in energy costs by converting to natural gas based heating systems. It is rational to believe that natural gas based heating systems with overall thermal efficiencies ≥50% would motivate the plastics industry to convert to gas-fired heating systems, provided these systems meet process requirements. Based on these considerations, an overall thermal efficiency goal of ≥50% was defined for the heating system explored during this study.

As mentioned earlier, infrared ovens represent the highest leverage heating system configuration for processing plastic film and sheet. This dictates that advanced gas-fired heating systems should be based on gas-fired radiant sources. In the last decade significant effort has been invested in the development of gas-fired radiant sources[3,4], which has resulted in commercially available units. Prior to this, however, gas-fired radiant sources were inefficient and would not have been capable of the efficiencies necessary to achieve the goal defined for the present study. This is without question one of the main reasons gas-fired heating systems have not been widely accepted in the plastics industry.

State-of-the-art commercially available gas-fired radiant sources are based on gas-fired radiant tubes. The radiant tubes are either solid ceramic, where combustion is contained within the tube, or porous ceramic, where combustion takes place in the pores adjacent to the external surface of the tube. Eclipse Combustion makes a commercially available gas-fired, single-ended, solid ceramic tube burner known as the Therm-Thief Silicon Carbide Radiant Auto-Recupe, which delivers thermal efficiencies in the range 70-75%. Alzeta Corporation makes a commercially available gas-fired, single ended, porous tube burner known as the Pyrocore Burner, which delivers thermal efficiencies as high as 90%. It should also be noted that these burners produce a radiant tube temperature of nominally 1000 K (1340 F). A blackbody temperature of 1000 K places the peak of the blackbody emission distribution at wavelength of nominally 3μm, which is in the wavelength region of maximum absorption for many plastics[2]. This is critical for maximum heating system efficiency. From an efficiency point of view, these technologies are well suited as a platform for developing gas-fired heating systems for processing plastic film and sheet. Although the Alzeta Pyrocore burner yields the most uniform tube temperature and greatest thermal efficiency, its exposed surface combustion characteristic makes it incompatible with certain plastics processes, such as solvent drying. Hence, a solid ceramic tube burner, such as the Eclipse Therm-Thief, is preferable as a radiant source for advanced heating systems for plastic film and sheet and therefore was used as the infrared source during the present study.

Although these gas-fired radiant tube sources have high efficiencies, they will not provide overall heating system efficiencies ≥50% or spatially uniform flux densities without a means of efficiently coupling and effectively imaging their infrared emission onto the plastic film or sheet being heated. The most promising means for achieving good coupling efficiency and imaging quality are diffuse or specular reflectors. Simple specular reflectors are commonly used for coupling/imaging optical radiation from visible sources to target areas or surfaces in lighting applications[5]. Diffuse reflectors are significantly less efficient than specular ones since radiation scattering off the reflector can return to the source. Cylindrical or parabolic specular reflectors are very efficient devices and can produce tailored flux density distributions on target surfaces when the source/target separation distance is large compared to the characteristic dimension of the emitting source. When this constraint is not satisfied, the emitting source blocks a significant amount of the radiation reflected off the reflector surface and also produces optical aberrations which make it difficult to obtain desired target surface flux density distributions. In order to achieve required film/sheet flux levels using gas-fired radiant tubes, the radiant tubes must be in close proximity to the target surface. Due to combustion flow constraints and the tube/target proximity criteria stated immediately above, the diameter of the radiant tube will be on the order the separation distance between the radiant tube and film/sheet surface. Based on these considerations, advanced gas-fired infrared heating systems will not satisfy the geometric constraint through use of simple reflector systems, and more complex systems must be adopted.

TDS encountered a similar situation when developing an optically pumped laser system, i.e., the characteristic dimension of the optical light source was on the order the separation distance between the source and the lasing medium being pumped. The efficiency of this laser system was increased significantly by using an advanced reflector design known as an involute reflector. The involute specular reflector is extremely efficient at extracting radiation from a cylindrical optical source when close proximity between source and target cannot be avoided, and can be tuned to give desired flux density distributions on target surfaces.

The novel gas-fired heating system concept explored during this study is based on coupling the infrared emission from a high efficiency gas-fired radiant tube to a target surface using advanced reflector technology. This forms the basis of TDS's response to the need for innovative approaches for heating systems that increase the competitive position of natural gas in the plastics industry. Figure 1.1 presents a sketch conveying the basic features of the TDS concept in the context of a common application, namely vacuum molding thermoplastics. It can be shown that the specular involute reflector illustrated in Figure 1.1 delivers all radiation emitted from the top side of the radiant tube to the plastic sheet stock surface, i.e., none of the reflected radiation is blocked by the radiant tube. This approach should efficiently couple the radiation from a gas-fired tube to a film/sheet surface and, at the same time, provide a mechanism which allows tailoring the flux density distribution on the film/sheet surface. Since the only losses posed by this reflector are due to imperfectly reflecting specular surfaces, which can be minimized by using properly polished aluminum based alloys, the high efficiency of gas-fired radiant tube burners should be preserved, suggesting that overall heating system thermal efficiencies ≥50% should be achievable.

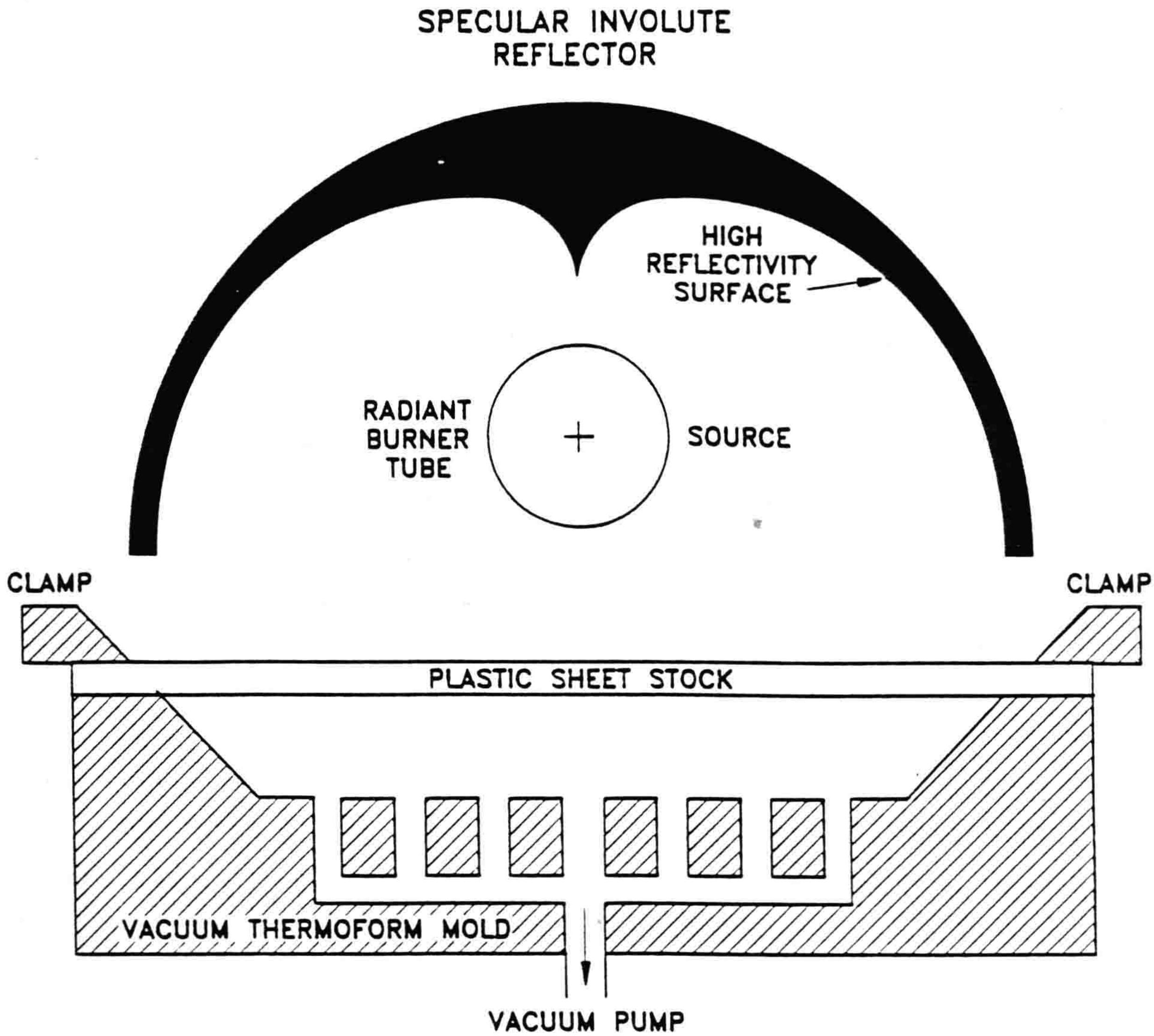

Figure 1.1. A High Efficiency Gas-Fired Proximity Heater for Vacuum Molding Thermoplastics.