ANNOUNCEMENT

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1. REPORT/PRODUCT NUMBER(s)

2. DOE AWARD/CONTRACT NUMBER(s)

DE-FG36-03GO13016

3. OTHER IDENTIFYING NUMBER(s)

GO13016

B. Recipient/Contractor

STORM Development LLC

C. STI Product Title

Advanced Process Heater

D. Author(s)

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E-mail Address(es):

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E. STI Product Issue Date/Date of Publication

03/07/2005 (mm/dd/yyyy)

F. STI Product Type (Select only one)

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X Final ☐ Other (specify)

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09/01/2003 Thru 12/31/2004

H. Sponsoring DOE Program Office

Golden Field Office

I. Subject Categories (list primary one first)

Industrial Technologies

Keywords

Industrial, Process, Silicon Carbide, Efficiency

J. Description/Abstract

see Executive Summary Attached

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Contact for additional information (contact or organization name to be included in published citations and who would receive any external questions about the content of the STI Product or the research contained therein)

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ANNOUNCEMENT

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Final Report

Final Report

Project Title: Advanced Process Heater

Covering Period: September 1, 2003 to December 31, 2004

Date of Report: March 7, 2005

Recipient: STORM Development, LLC.

Award Number: DE-FG36-03GO13016

Working Partners:

STORM Development LLC; Penn State University, Erie; Spinworks LLC; SyCore, Inc.

Cost-Sharing Partners: STORM Development LLC; Spinworks LLC; SyCore, Inc.

Contact: Thomas D. Briselden, 814-440-2604, tbriz@att.net

Project Team: DOE HQ Program Manager, Lisa Barnett
DOE Field Project Officer, Steve Sargent

EXECUTIVE SUMMARY

The *Roadmap for Process Heating Technology* (March 16, 2001), identified the following priority R&D needs: *Improved performance of high temperature materials; Improved methods for stabilizing low emission flames; Heating technologies that simultaneously reduce emissions, increase efficiency, and increase heat transfer*".

This Category I award entitled "Proof of Concept of an Advanced Process Heater (APH) for Steel, Aluminum, and Petroleum Industries of the Future" met the technical feasibility goals of: (1) Doubling the heat transfer rates (2) Improving thermal efficiencies by 20%, (3) Improving temperature uniformity by 100 °F and (4) simultaneously reducing NO_x and CO₂ emissions. The APH address EERE's mission priority of increasing efficiency/reducing fuel usage in energy intensive industries.

One component of the APH, the SpyroCor™, was commercialized by STORM Development's partner, Spinworks LLC. Over 2000 SpyrCors™ were sold in 2004 resulting in 480 million BTU's of energy savings, 20% reduction in NO_x and CO₂ levels, and 9 jobs in N.W. Pennsylvania. A second component, the HeatCor™, a low-cost high-temperature heat exchanger will be demonstrated by Spinworks in 2005 in preparation for commercial sales in 2006.

The project occurred in the 21st Congressional District of Pennsylvania. Once fully commercialized, the APH energy savings potential is 339 trillion BTUs annually in the U.S. and will process 1.5 million more tons annually without major capital equipment expenditures. Spinworks will commercialize the APH and add over 100 U.S. workers.

To accomplish the objective, STORM Development LLC teamed with Penn State University, SyCore, Inc, Spinworks LLC, and Schunk-INEX, Inc. The project consisted of component engineering and integration of the APH followed by parametric testing. All components of the system were tested in a lab furnace that simulates a full scale industrial installation. The target areas for development include: (1) Scale up STORM's *Finned Stabilized Combustion*, (2) Optimization of SyCore's *SiGr Inserts* such that the heat transfer on the exhaust leg will match the high luminosity burner leg., (3) Evaluation of the heat transfer characteristics of Schunk-INEX's finned composite tubes as a heat exchanger, and (4) Design of a system to monitor all components of the APH and control its performance such that the objectives are met.

PROJECT DESCRIPTION

Project Goals:

The original goal of the Advanced Process Heater (APH) is to exceed the performance of current heating technology by: (1) Doubling the heat transfer rates (2) Improving thermal efficiencies by 20%, (3) Improving temperature uniformity by 50 °F to 100 °F and (4) simultaneously reduce NO_x and CO₂ emissions.

To accomplish these goals, STORM Development LLC will team with Penn State University, SyCore, Inc, Spinworks LLC, and Schunk-INEX, Inc. on a Category I project. The project will consist of component engineering and integration of the APH followed by parametric testing. All components of the system will be tested in a lab furnace that simulates a full scale industrial installation. The target areas for development include: (1) Scale up STORM's *Finned Stabilized Combustion*, (2) Optimization of SyCore's *SiGr Inserts* such that the heat transfer on the exhaust leg will match the high luminosity burner leg., (3) Evaluation of the heat transfer characteristics of Schunk-INEX's finned composite tubes as a heat exchanger, and (4) Design of a system to monitor all components of the APH and control its performance such that the objectives are met.

Project Objectives:

In order to achieve the efficiency, heat release, and emissions targets, The Advanced Process Heater addressed the following technical issues:

1. STORM's *Finned Stabilized Combustion* will be required to increase the combustion intensity in the radiant tube by 150% while promoting temperature uniformity of ± 10 °F and low emissions (< 10 ppm).

Traditionally with high intensity burners, radiant tube efficiency is reduced due to short residence times of combustion gases and low heat transfer coefficients on the inside of the tube.

2. SyCore *SiC Inserts* will increase the heat transfer on the exhaust leg to match the high luminosity burner leg. Heat Transfer coefficients need to be increased by 225% with the use of high emissivity inserts.

The use of SyCore Inserts is a proven method for increasing the heat transfer off the exhaust leg of a radiant tube. However, its efficiency impact is generally limited to 20% since it can not reduce exhaust temperatures below the furnace or process heater temperature.

3. *Finned/Multi-Pass Composite Heat Exchanger* will be required to preheat combustion air to temperatures over 1200 °F in order to produce an overall thermal efficiency above 75%. In doing so, an energy savings exceeding 50% can result.

High Combustion Intensities generated by the burner, High Heat Transfer Rates generated by the SyCore Inserts, and High Preheat Air Temperatures generated by the recuperator all need higher operating temperatures than the 2100 °F limit of metal alloy tubes.

4. A Schunk-INEX *Composite U-Tube* will be required to operate at temperatures of 2450 °F while tolerating extreme thermal shock. Only the burner leg of the tube will need to be finned such that the high intensity flame can be established within the fins.

Flame stabilization in a finned tube was proven at Cleveland State University. It promotes exceptional temperature uniformity (± 2 °F) and low NO_x levels (< 10 ppm) due to high heat transfer surface areas.

Work Performed:

Summary:

Task 1 – Scale up of Flame Stabilization Concept

- 1.1 Design Finned Tube Heating System
 - Used a clear quartz tube to provide a direct method for evaluating flames.
- 1.2 Perform Parametric Testing
 - Used helical inserts in place of finned tube to enhance flame stability. Achieved heat flux of 153 BTU/hr-in³
 - Purchased thermal imaging camera for temperature uniformity study.
- 1.3 Analyze Results of Flame Stabilization Scale up
 - New burner was designed utilizing single tube burner for both air and fuel mixture delivery and hollow helical shape.

Task 2 – Design and Test APH for Project Goals

2.1 Design APH

- Incorporated preliminary designs for SiC Heat Exchanger.
- Increased surface area of new heat exchanger by a factor of 2.

2.2 Enhance Test Furnace Capabilities

- Incorporated thermal imaging camera in furnace temperature measurement system.
- Installed Advanced gas analysis system to measure NO_x, CO, CO₂, O₂, and temperature.

2.3 Install and Test APH and Analyze Results

- Used SiC Heat Exchanger to obtain pre heat temperatures up to 850°F which increased efficiency to over 70%.
- Obtained U-tube uniformity within 100°F.

2.4 Modify System and Retest

- Modified heat exchanger to single piece design.
- Reduced NO_x levels to under 90 ppm.

Task 1.1 Design Finned Tube Heating System

A straight 4.5 inch (114 mm) diameter straight finned tube heating system was designed in the month of September 2003. A technical representation of the system is shown in Figure 1. Key design features of the system include: (1) use of a clear quartz tube to allow for flame visualization, (2) identification of an alternate method to simulate the tube fins, and (3) incorporation of an active loading system into the test furnace.

The active loading system duplicates the exact material loading conditions of an industrial furnace. Stainless steel chains are moved through the test furnace using a rotary drum. The steel is heated to 1800° F then quenched and returned back through the furnace. This system provides a very close approximation of the heat transfer conditions present in an industrial furnace. The impact of the finned heating system can be properly analyzed under these conditions.

Figure 1: Technical representation of the straight finned tube heating system. The clear quartz radiant tube will be used to evaluate flame stabilization. The loading system and furnace geometry represents an accurate heat transfer simulation of an industrial furnace.

Task 1.2 Perform Parametric Testing

An initial series of tests were performed to establish flame stability and temperature uniformity. The flame was stable over a wide range of air fuel ratios from 10:1 to 16:1. Air and fuel distribution was accomplished by using a single tube. Air flowed to the outside of the tube, and natural gas flowed down the middle. Standard spark ignition and flame safety equipment was used during the test.

Previously, a temperature uniformity of $\pm 18^\circ\text{F}$ (10°C) and a heat flux of 125 BTU/hr-in^2 was achieved. The goal for the project was $\pm 10^\circ\text{F}$ (5.5°C) and 150 BTU/hr-in^2 . Parametric testing continued on the system to identify the key parameters that impact these goals. The result was a temperature uniformity of $\pm 10^\circ\text{F}$ (5.5°C), shown below (Figure 2), and a heat flux of 153 BTU/hr-in^2 . This was achieved using a variable twist rate design from 63° to 32° .

STORM was going meet the project goals by stabilizing the flame within short fins attached to the tube. The scale-up of the tube from 2" I.D. to 4.5" I.D. resulted in a narrow range of operation and an un-stable flame. STORM has prepared a disclosure on a unique expansion of this concept. The reader may contact the PI to further discuss this concept.

Figure 2: Temperature profile along straight tube operating at a heat flux of $153,260\text{ BTU/hr-in}^2$.

To assist in the analysis of the flame stabilization concept, STORM purchased an infrared thermal imaging camera. This camera is used to provide a complete thermal profile of the tube and heat flux measurements (Figure 3). The camera has been extensively used in the APH test furnace.

Figure 3: Infrared image of a flame stabilized inside a radiant tube. The IR image will allow the identification of “hot spots” that in turn will be used to make design improvements.

Task 1.3 Analyze results of flame stabilization scale-up

Data from Task 1.2 was analyzed and used to make a significant modification to flame stabilization concept. Early tests required the use of a partial premix system to stabilize the flame. This concept eliminates partial premix, allows for a larger range of turndown, expands the allowable twist rates, and makes flame detection easier.

The new burner design was incorporated to increase flame stability. The new burner consists of a single tube mixture system where air flows down the outside of the tube, while gas flows through the middle. A SpyroCor is incorporated into the design such that the proper air and gas flow is distributed to maximize flame stability.

Task 2.1: Design APH

The primary focus of the APH design was on the heat exchanger. This encompassed two areas: (1) increasing heat transfer surface area per unit volume, and (2) making a thin walled heat exchanger out of silicon carbide. A second concept disclosure has been prepared for the Department of Energy. Two key goals were achieved: (1) a 1/16" thick silicon carbide heat exchanger wall was achieved and (2) an increase in heat transfer surface area by a factor of 2.5.

Task 2.2 Enhance Test Furnace Capabilities

STORM in partnership with Spinworks began enhancing the test furnace shown in Figure 5. This furnace is used to test the Advance Process Heater. The APH combines the flame stabilization method with a silicon carbide radiant tube and an advanced multi-pass heat exchanger. The final elements left to the test furnaces completion was incorporating the thermal imaging camera and advanced gas analysis system for measuring NO_x, CO, CO₂, O₂, and temperature. Figure 6 shows a typical image of the APH in operation, taken with the thermal camera.

Figure 5: Advanced Process Heater Test Furnace utilizing a silicon carbide composite radiant U-tube. The furnace utilizes an active loading system to simulate a real industrial operating environment of 1800 °F (982 °C). The tube is full scale. One difference between this system and one found in a steel mill is the number of tubes.

Figure 6: A typical image from the thermal imaging system which was incorporated in the test furnace.

Task 2.3 Install and Test APH and Analyze Results

The installed APH is shown in Figure 7. The initial scope of work included purchasing a finned multi-pass heat exchanger from either Blasch or Schunk-INEX. Due to a change of direction in these companies, it was necessary for STORM and Spinworks to develop its own heat exchanger. The innovative heat exchanger utilizes silicon carbide material for high temperature operation and excellent thermal shock properties. Its unique design increases the heat transfer surface area by 2 to 5 times that over traditional heat exchangers with minimal pressure drop. The current design obtained preheat air temperatures up to 850 °F.

A proof-of-concept was performed on the helical heat exchanger. A ½ length (due to manufacturing furnace limitations) heat exchanger was tested with a surface area of two and three times standard. An effectiveness of 33% and 47% were achieved. Based on these results, a full length heat exchanger with a 3 times standard surface area will produce an effectiveness approaching 80%. Pressure drops on the order of 5 to 10 inches w.c. resulted.

The proposed heat exchanger for the APH will closely couple the heat exchanger to the radiant tube and flame stabilizer to minimize these losses and increase the overall effectiveness of the heat exchanger.

Figure 7: Installation of the APH in the high temperature test furnace showing the burner and SiC recuperator.

Task 2.4 Modify System and Retest

Modifications to the APH focused on changing the heat exchanger to obtain preheat air temperatures of 1200 °F.

The last quarter of the project primarily focused on the multi pass heat exchanger. Significant modifications were made to improve the overall efficiency. The heat exchanger was converted to a shared web to promote better heat transfer. Data from continued testing of the APH with the shared web heat exchanger proved that 850°F pre-heat temperatures can be easily achieved. NO_x levels dropped dramatically to 90 ppm and lower.

Patent disclosures are being prepared for the heat exchanger concept. For further information on the heat exchanger, please contact the P.I., Tom Briselden at tbriz@att.net.

Appendices

- Appendix A. Final Task Schedule
- Appendix B. Final Spending Schedule
- Appendix C. Final Cost Share Contributions
- Appendix D. Energy Savings Metrics

Appendix A

Final Task Schedule

Task Schedule

Task Number	Task Description	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
Milestone 1	Scale up of flame stabilization concept.	12/31/03	01/31/04			
Task 1.1	Design finned tube heating system	05/31/03	10/31/03	10/31/03	100%	
Task 1.2	Perform parametric testing	10/31/03	12/31/03	02/15/04	100%	
Task 1.3	Analyze results of flame stabilization scale-up	12/31/03	01/31/04	04/15/04	100%	
Milestone 2	Design and Test APH for project goals.	12/31/04				
Task 2.1	Design APH	02/29/04		05/30/04	100%	
Task 2.2	Enhance Test Furnace Capabilities	03/31/04		05/28/04	100%	
Task 2.3	Install and Test APH and Analyze Results	08/31/04		9/31/04	100%	
Task 2.4	Modify System and Retest	012/31/04		12/31/04	100%	

Project Period: 04/01/03 to 12/31/04

Current Quarter: 10/01/04 to 12/31/04

Spending Schedule

Task	Approved Budget	Project Expenditures	
		<i>This Quarter</i>	Cumulative to Date
Task 1.1 – Design finned tube heating system	3,929	0	3,929
Task 1.2 – Perform parametric testing	15,122	0	15,122
Task 1.3 – Analyze results of flame stabilization scale-up	2,658	0	2,658
Task 2.1 – Design APH	6,458	0	6,458
Task 2.2 – Enhance test furnace capabilities	18,568	0	18,568
Task 2.3 – Install and test APH and analyze results	26,083		26,083
Task 2.4 – Modify system and retest	4,864	4864	4864
Total	77,681	4864	77,681
DOE Share	40,000	0	40,000
Cost Share	37,681	4864	37,681

Appendix C

Final Cost Share Contributions

Cost Share Contributions

Funding Source	Approved Cost Share		This Quarter		Cumulative to Date	
	Cash	In-Kind	Cash	In-Kind	Cash	In-Kind
STORM Development	9,466	13,300		4864	9,466	19,041
SyCore, Inc.		5,340				3,225
INEX		9,575				5,950
Penn State University	0					
Total	9,466	28,215	2,600	3,911	9,466	28,216
Cumulative Cost Share Contributions					37,681	

Appendix D

Energy Savings Metrics

According to market research by The Gas Research Institute, the market consists of 250,000 radiant tubes in 25,000 furnaces. The unit chosen for analysis is 10 radiant tubes or 10 APHs processing 5 tons of metal per hour. This would represent the loading of a typical steel processing furnace such as strip annealing or heat treating. The energy required to simply heat this amount of metal to 1400 °F with a .12 BTU/lb-°F specific heat is 1.3 million BTU/hr of energy (this number does not include an efficiency factor). The table below represents the four scenarios with typical efficiency factors: (1) basic unit - 35%, (2) unit with standard energy enhancements such as a plug heat exchanger – 50%, (3) state-of-the-art energy efficiency unit – 65%, and (4) application of the APH – 85%.

	Basic Unit	Standard	State-of-the-art	Advanced Process Heater
Efficiency	35%	50%	65%	85%
Radiant tubes/unit	10	10	10	10
Production rate, lb/hr	8000	8000	8000	8000
Specific Heat, BTU/lb-F	0.12	0.12	0.12	0.12
Process Temperature, F	1400	1400	1400	1400
Net Energy, BTU/hr	1,344,000	1,344,000	1,344,000	1,344,000
Gross Energy per Unit, BTU/hr	3,840,000	2,688,000	2,067,692	1,581,176
Annual Operating Hours	6,000	6000	6000	6000
Annual Energy Use per Unit, million BTUs	23,040	16,128	12,406	9,487
Annual Energy Use for Market, trillion BTUs	576	403	310	237
Annual Energy Savings Matrix, trillion BTU's				
Basic Unit vs. Std. S-O-A, APH		173	266	339
Standard vs. S-O-A, APH			93	166
State-of-the-art vs. APH				73
ALL(weighted) vs. APH	60%	25%	15%	256

A basic unit is a simple U-tube and burner combination. A standard efficiency upgrade would include a plug-in type heat exchanger and perhaps a burner upgrade. The state-of-the-art unit would be an advanced tube/heat exchanger design. These units would incorporate finned heat exchanger components and recirculation burner designs.

The annual energy savings matrix compares the basic unit to a standard, state-of-the-art and APH concepts. The annual fuel saving potential for process heating equipment is between 73 and 339 trillion BTU's. This is based on converting 250,000 radiant tubes. With an average energy cost of \$5/million BTU, the potential savings to the industrial market using radiant tubes is between 254 million and 1.7 trillion dollars.

An estimated 60% of the market consists of a basic radiant tube, 25% with standard up-grades, and the remaining 15% state-of-the-art. A per unit analysis is shown in the following table for the years 2008 through 2015.

YEAR	2008	2009	2010	2011	2012	2013	2014	2015
GROWTH RATE		200%	150%	100%	75%	50%	25%	10%
ANNUAL SALES	500,000	1,500,000	3,750,000	7,500,000	13,125,000	19,687,500	24,609,375	27,070,313
UNITS/YEAR	25	75	188	375	656	984	1,230	1,354
ENERGY SAVINGS/UNIT, million BTU's	19,717	19,717	19,717	19,717	19,717	19,717	19,717	19,717
ANNUAL ENERGY SAVINGS, trillion BTU's	0.5	1.5	3.7	7.4	12.9	19.4	24.3	26.7
CUMMULATIVE ENERGY SAVINGS, trillion BTU's		2.0	5.2	11.1	20.3	32.3	43.7	50.9