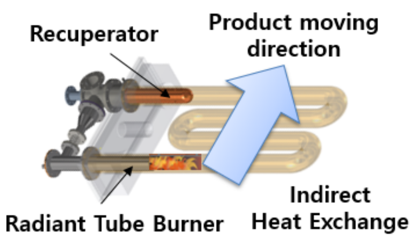
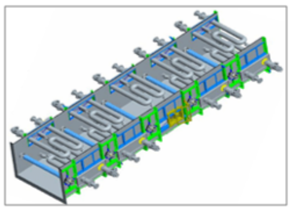
1. Background

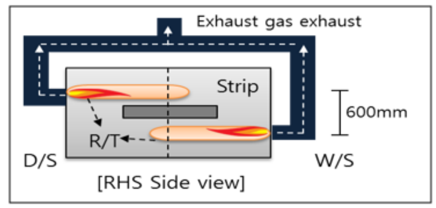
Background

- ○ Pohang Steelworks consumes approximately 100 Million US dollars of natural gas for fuel in reheating furnace and annealing furnace, etc.
- ○ Energy saving of natural gas is essential not only to reduce energy cost but also to reduce CO_2 emissions.
- ○ Silicon steel plant in Pohang steelworks has 495 radiant tube burners using 82 Millions Nm^3 of natural gas. Its furnace temperature is 950 ~ 1,050℃ which is the highest and the most severe temperature conditions in terms of applying innovative technology.





[Configuration]



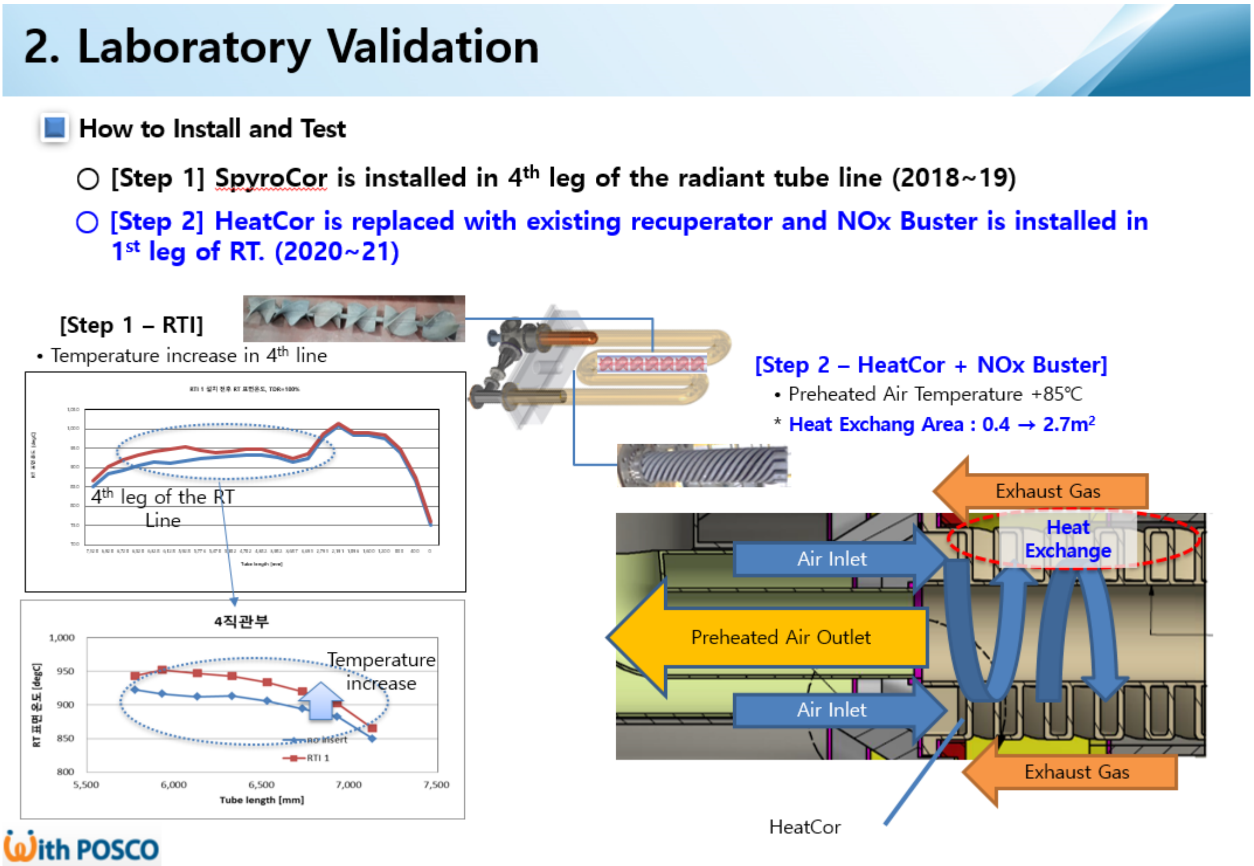
[Simple Diagram]

With POSCO

Our focus today is on enhancing radiant tube combustion systems in continuous galvanizing and annealing lines, where we are interested in reducing fuel, Carbon, and NOx to help companies meet their near term 2030 and long term 2050 sustainability goals.

To help foster near term implementation with excellent ROIs, solutions will be discussed that are retrofit in nature and require a total solution including advanced thermal designs, computational modeling, and testing.

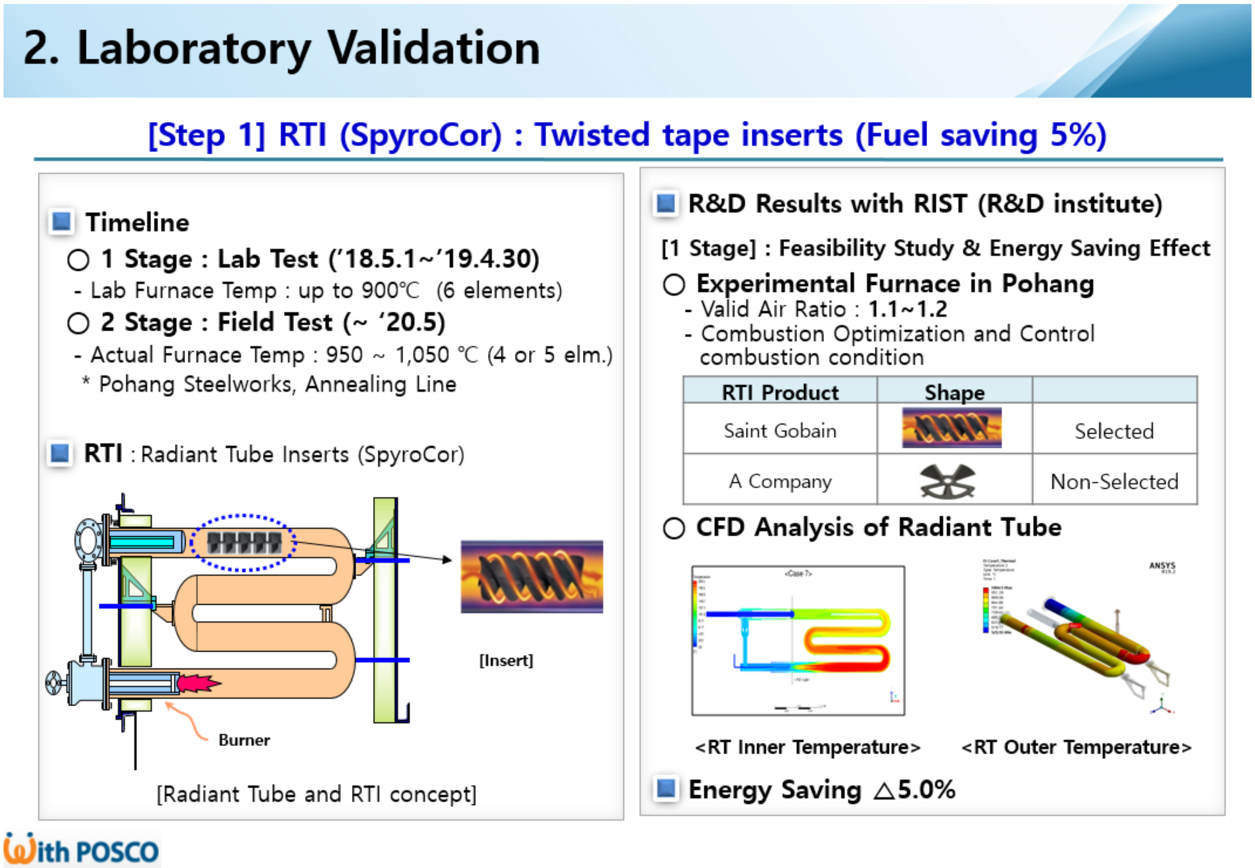
A further goal is that these designs have minimal impact on the burner and control systems.



A single radiant tube will typically use 3 million cubic feet of natural gas a year, generate 150 metric tons of carbon, and 565 lbs of NOx.

If we apply a total solution to this that reduces energy by 20% and NOx by 15%, the impact is impressive when applied to 100,000 radiant tubes and will go a long way to meeting the worlds environmental goals.

1.6 billion cubic feet of natural gas, 3 mega tons of carbon, and 9 kilo tons of NOx can be achieved through adopting relatively simple but innovative concepts.



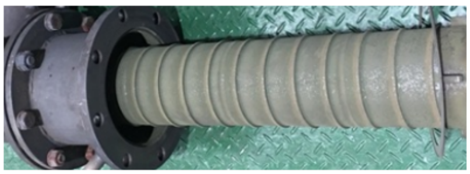
In order to achieve the energy, carbon, and NOx reduction goals, the material plays a critical role in allowing these design to operate effectively in extreme environments. Namely, high operating temperature to meet all applications, thin walls, high thermal conductivity and emissivity for excellent heat transfer, a non-porous low oxidation material matrix is required. These elements combined help reduce thermal shock resulting in a perfect material for long life in a combustion environment using both NG and COG.

3D printing allows us to move to advanced thermal designs that cannot be made with traditional methods of slip-casting, pressed, extruded and even injection molded.

2. Laboratory Validation

[Step 2] The New Recuperator : 3D Printing (Fuel Saving 11.5%)

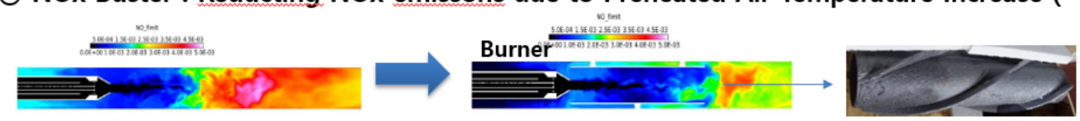
- **NDA between Saint-Gobain and POSCO**
  - ○ **[Saint-Gobain] Providing and Redesigning 3D Printing Recuperator and NOx Buster Cooperating Lab and Field Test and Experts supporting**
  - ○ **[POSCO] Supervising Lab and Field Test and Redesigning 3D Printing Recuperator and NOx Buster**
- **Comparison of Recuperators**
  - ○ **Heat Exchange Area : 0.4 → 2.7m^2 (Fin Type → Twisted Channel Type)**



<Previous Recuperator : 0.4m^2>

<The New Recuperator : 2.7m^2>

- ○ **NOx Buster : Reducting NOx emissons due to Preheated Air Temperature Increase (+85℃)**



<Before> <After> <Burner Side : NOx Buster>

With POSCO

In a report generated by the department of energy, they identified the theoretical practical reduction of energy as going from 1MMBTU/ton to .65. This corresponds to a CO_2 reduction per ton from 117 to 76 lbs. The South Cost Air Quality Management District which seems to be the most stringent in the US is targeting less than 40ppm for industrial heating processes.

We want to enhance the radiant tube heat transfer, improve the heat exchanger effectiveness and simultaneously reduce NOx.

Several of these statements can be contradictory. As an example, increased efficiency can require higher levels of pre-heat air which, in not managed properly can increase NOx.

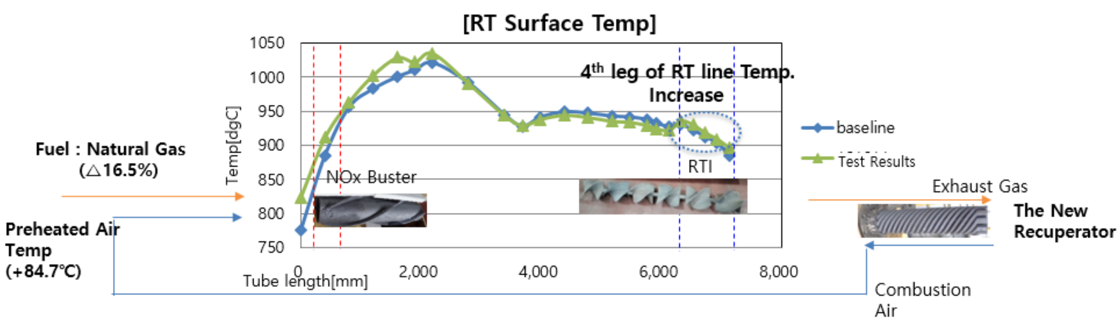
2. Laboratory Validation

[Overall Test Results] RTI + The New Recuperator (Fuel Saving 16.5%)

Overal Test Results

- ○ **RTI + The New Recuperator : Fuel Saving △16.5%** (**RTI △5%, The New Recupeator** △**11.5%**)
- ○ NOx Emissions : 134 → 111 ppm (@O2 11%) Due to NOx Buster

Results	**TDR** (%)	**Radiant Tube Efficiency**(%)	**Rediant Tube Ralative Comparion** (%)	**Preheated Air Temperature**(℃)	**Nox @O2 11%**(ppm)
Before (A)	100	36.97	100.0	448.3	134
After (B)	**83.5**	**45.03**	**121.8**	**533**	111
(B – A)	**△16.5**	+8.1	+21.8	**+84.7**	**△23 (△17.2%)**



With POSCO

3. Field Validation

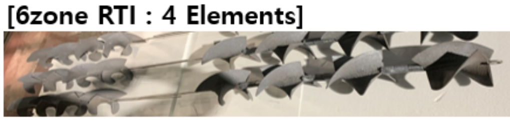
RTI 68 Sets : Energy Saving △7.9%

Installation of RTI 68 sets in Annealing Furance ('19.11, '20.12)

Zone	RT Burner (EA)	Burner Capacity (kcal/hr)	RTI Installation (EA)	Installation Date
2zone	12	145,000 x 12	12 (RTI : 4 Wings)	'20.12
3zone	10	145,000 x 10	10 (RTI : 4 Wings)	'20.12
4zone	10	145,000 x 10	10 (RTI : 5 Wings)	'20.12
5zone	10	145,000 x 10	10 (RTI : 5 Wings)	'19.11
6zone	14	145,000 x 2, 125,000 x 12	14 (RTI : 4 Wings)	'19.11
7zone	12	125,000 x 12	12 (RTI : 5 Wings)	'20.12

[5zone RTI : 5 Elements]

[6zone RTI : 4 Elements]

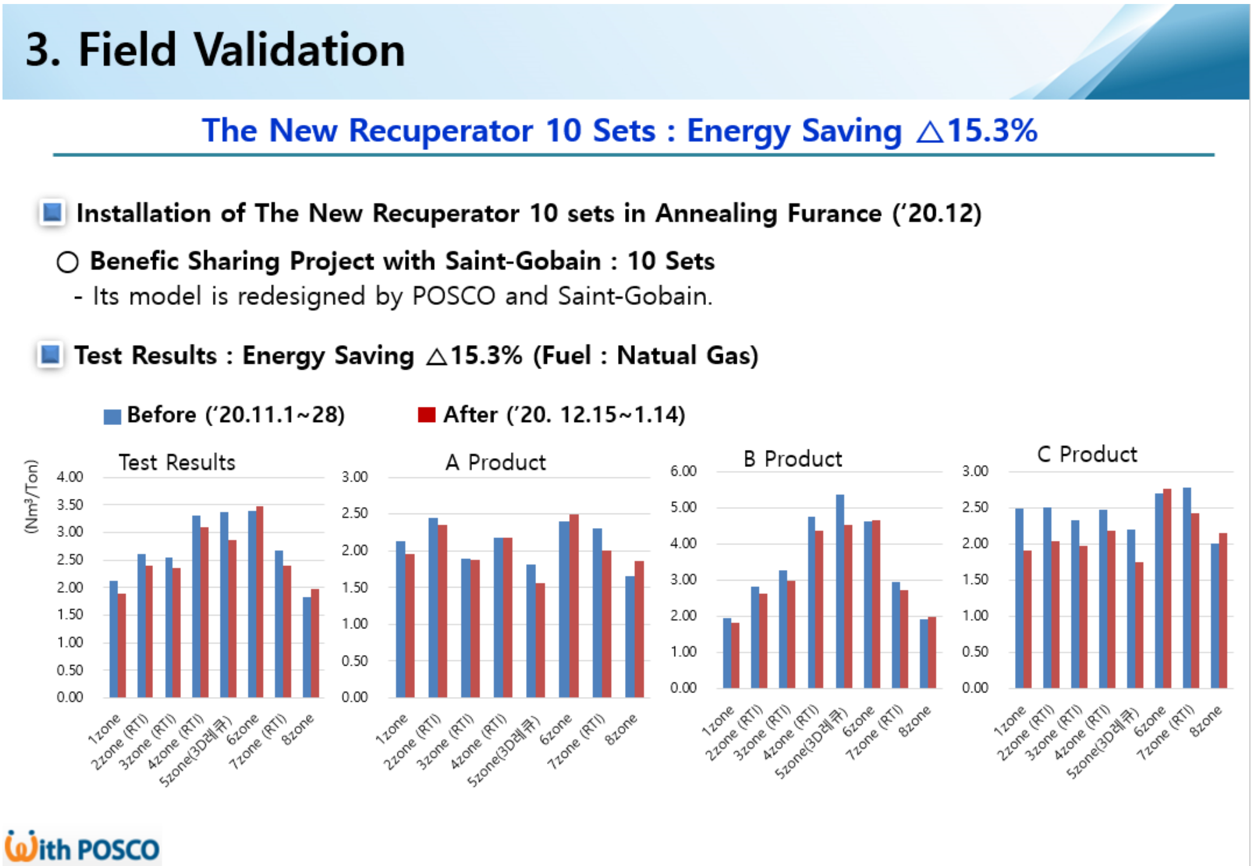


[4th Line : Installed in right before Recuperator]

Energy Saving △7.9%

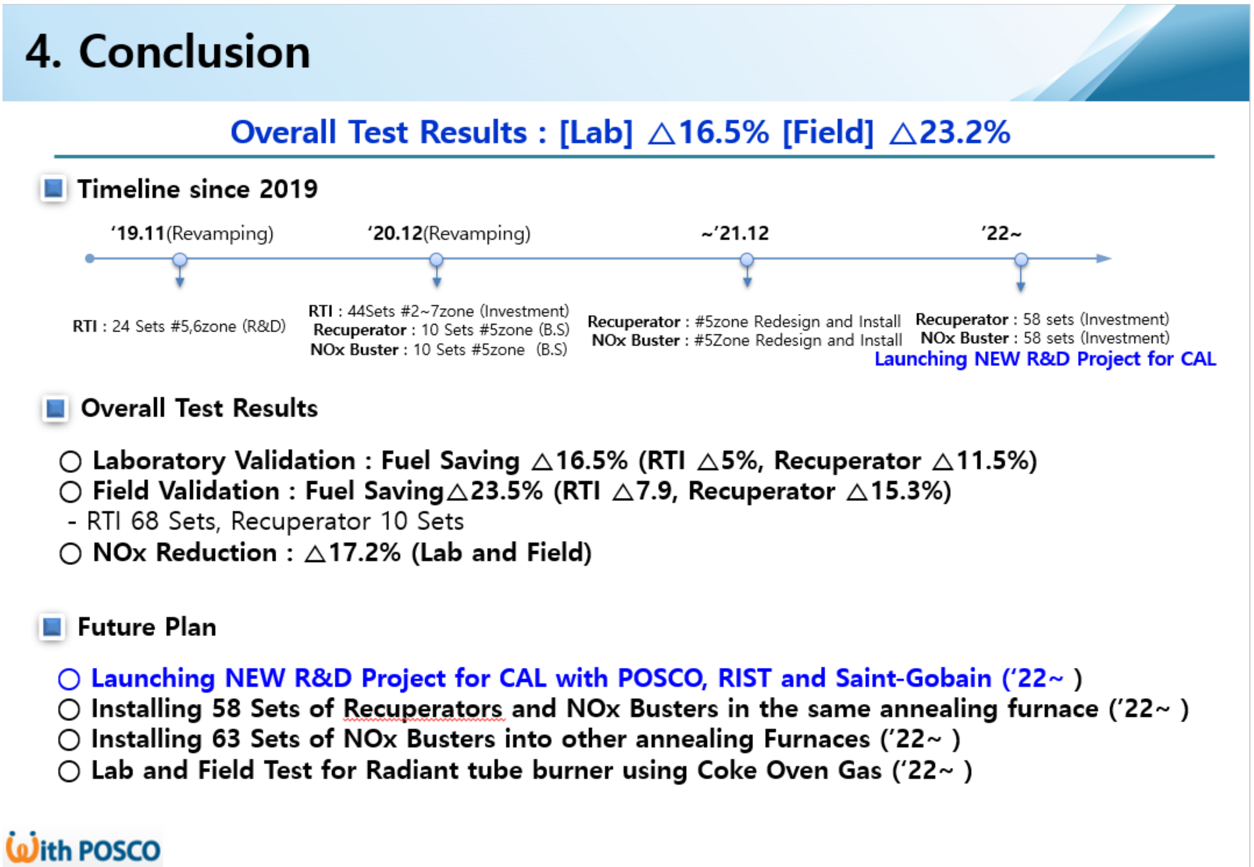
With POSCO

The use of spiral twisted tape inserts provide an effective means, when combined with additive manufacturing, to make a device that absorbs exhaust energy and re radiates similar to a flame. Interestingly, we find that a ratio of the surface area of the tube to that of the twisted tape being approximately 1 gives the ideal balance of radiation and convection in the exhaust leg. Additive manufacturing, as compared to slip cast or injection molding, allows the twist rate to be easily modified and optimized for a given radiant tube. While increasing the twist rate further enhances the heat transfer, overheating may occur. However, this may be an advantage in for example a radiant tube made of ceramic. Typically, 3-18% energy and CO_2 reductions occur with minimal pressure drop.



Recuperators are design as simple straight tubes, or enhanced with fins or bumps. With this type of design in a parallel flow heat exchange design, overall system efficiencies are typically between 60 to as high as 68%.

Enhancing this design needs to address both improvement to surface area and the heat transfer coefficient in order to minimize pressure drop to the system.



Extending the concept of a twisted tape to that of a heat exchanger, a twisted channel is showing to be an effective means of increasing both surface area and overall heat transfer coefficient simultaneously.

The twisted channel imparts a velocity vector perpendicular to the heat transfer surface that acts as jet impingement. This increases the Nusselt number and the overall heat transfer coefficient by 25% at the midrange of the design flow and corresponding Reynolds number.

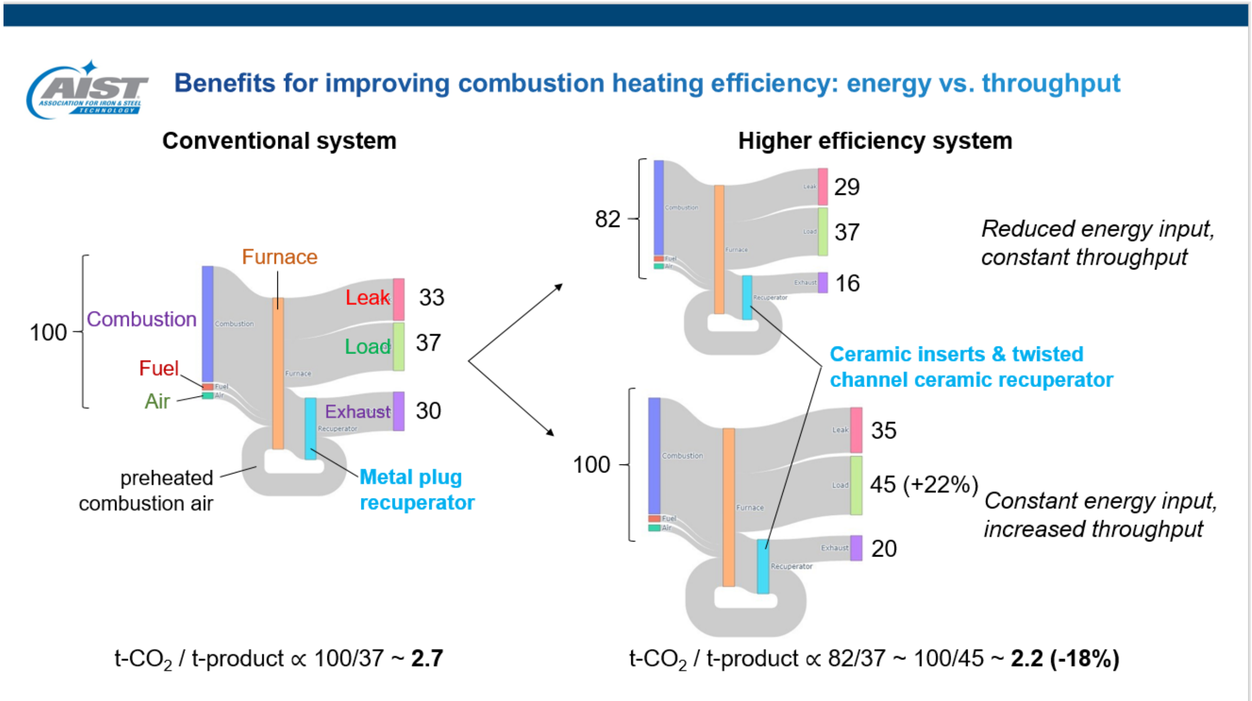
Increasing the surface are, with the assistance of additive manufacturing, allows for a significant change in surface area as compared to fins and bumps. A typical tube recuperator will have a surface are of 450 in^2. A shallow twist 3 fin design can match this surface are. However, when increasing both the number of twisted channels and twist rates, a surface area of 2X is achieved.

The corresponding improvement in heat transfer coefficient allows overall radiant tube efficiencies to approach 85%., thus 5-30% energy and carbon reduction can be realized. The combined reduction of flow rate and improved heat transfer coefficient and counter flow design allows pressure drops to be minimized in the overall system.

Initially, internal exhaust gas recirculation was explored as an effective means of reducing NOx. While reduction in the range of 35% to 50% was achieved, it was limited to a few burners, or required modification to existing burners. Here is a visual demonstration of the concept.

Due to the impact on the burner and control system, a computational evaluation along with laboratory validation identified an effective means of NOx reduction with minimal impact on the burner or control system.

Flame splitting is showing the ability to reduce NOx by up to 70% in a variety of exiting burners. This includes nozzle mix, partial premix, air or gas staged combustion and low NOx burners, with and without EGR.

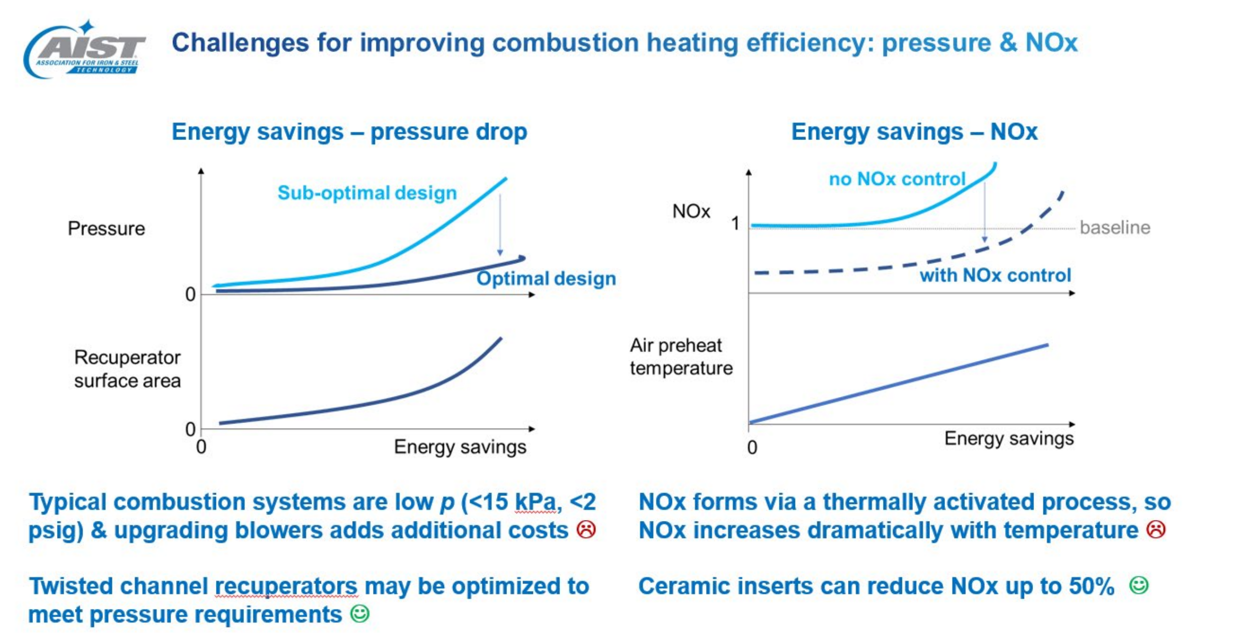


Improving heating efficiency helps to reduce energy consumption or increase product throughput or some combination of two, depending on operating conditions. To illustrate this, consider the 3 Sankey diagrams shown here illustrating the energy flows in a recuperated furnace. This furnace could be a continuous annealing/galvanizing line utilizing radiant tube heating, or really any indirectly or directly fired heating process with recuperation.

The left diagram shows energy flows for a conventional metal plug-recuperated system. Here energy inputs–fuel, air, and their mutual combustion heat – are 100 arbitrary energy units. And heat flowing to the load (e.g. steel strip), exhaust, and leaks in the furnace are shown.

On the right consider 2 extremes for a system utilizing high efficiency ceramic inserts and recuperators. The top furnace operates at similar throughput to the conventional system; here, 18% energy savings are realized. Similarly, the bottom furnace operates at similar energy input while adding ~22% throughput. Real systems likely operate with some mix of the two.

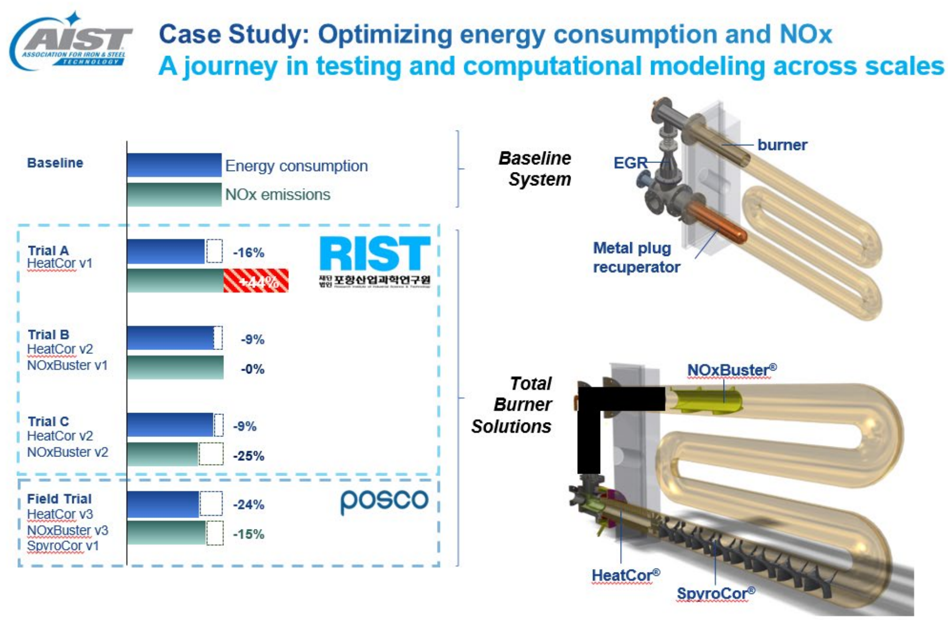
We will focus on energy savings in the remainder of this talk, but the key point here is that energy savings and throughput are related benefits of higher heating efficiency. And, in terms of specific CO_2 emissions measured in ton CO_2 per ton product which is proportional to the ratio of input and load energies any combination of energy savings and throughput with the higher efficiency systems reduces specific CO_2 emissions, 18% in this case.



The two main challenges for improving the efficiency of recuperated combustion heating systems are pressure and NOx. Here, I schematically show how pressure (that is the pressure drop from the blower to the exhaust across a radiant tube or zone pressure drop, for example), recuperator surface area, NOx emissions, and preheat air temperature vary with energy savings or energy efficiency.

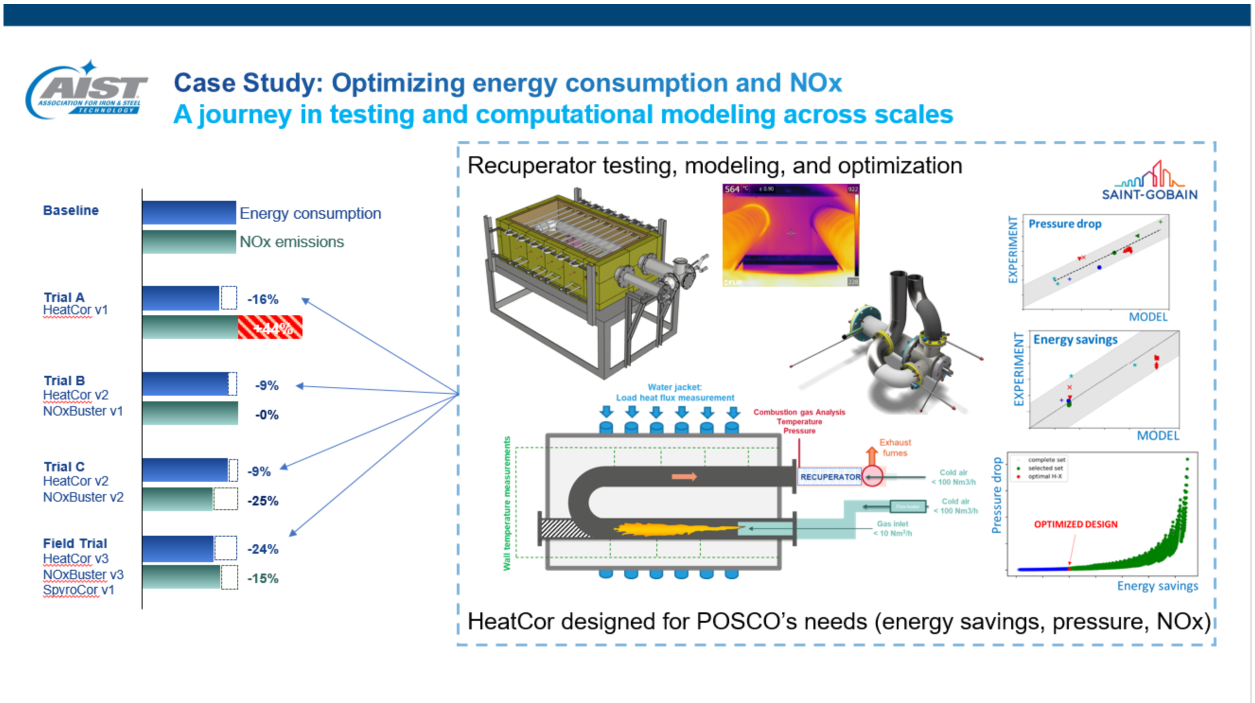
Left: As energy savings is increased, recuperator surface area increases, which in turn increases pressure drop of the combustion system. Typical blower systems operate at low pressure, and upgrading adds costs. Fortunately, twisted channel recuperators may be optimized using computational modeling to minimize pressure drop and avoid blower upgrades while providing energy savings.

Right: Reducing energy consumption by recuperation increases the preheated combustion air temperature. Because NOx is a thermally activated process, you may find significant increases in NOx at higher flame temperatures while targeting additional energy savings. Fortunately, this may be avoided by utilizing ceramic inserts to reduce NOx by up to 50%.

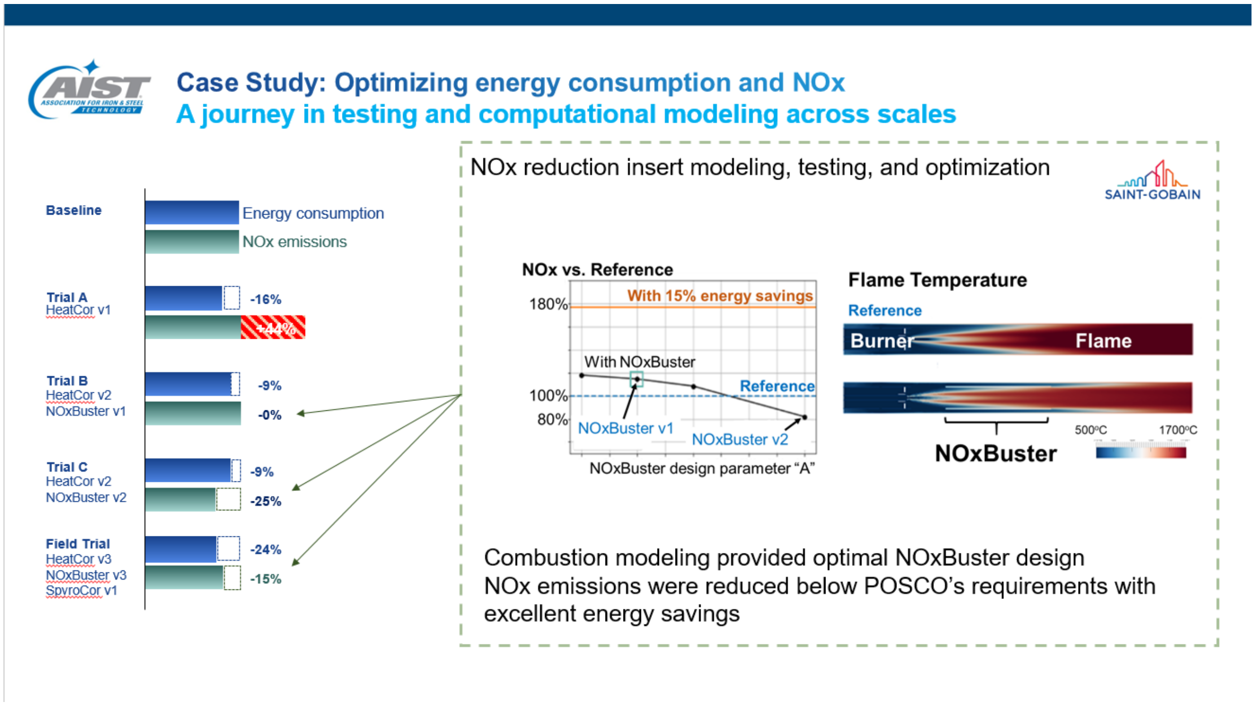


To illustrate the benefits and challenges in action, Saint-Gobain assisted POSCO to save 24% on energy and reduce NOx emissions by 15% in a field installation.

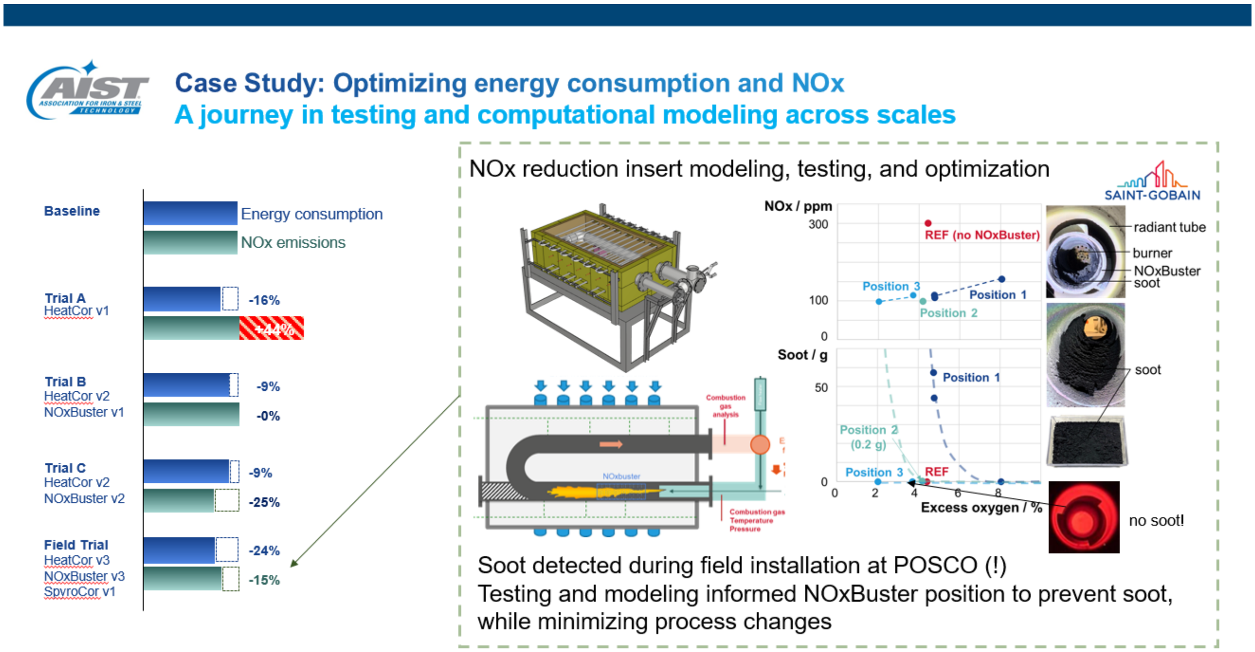
Results from a series of trials at RIST, a research affiliate of POSCO, and POSCO are shown on the left. The baseline system consists of a W-tube, burner, EGR, and metal plug recuperator. The remaining trials utilize various configurations of HeatCor, NOxBuster, and SpyroCor illustrated here.



Leveraging Saint-Gobain's pilot scale test furnace and previous experience with HeatCor and SpyroCor, designs may be optimized with modeling and rapidly manufactured to achieve the target performance. Notice in Trial A, HeatCor v1 without a NOxBuster provides 16% energy savings while increasing NOx by more than 40%. This is a direct result of the higher combustion air preheating with the HeatCor.



To combat higher NOx, the NOxBuster, a ceramic insert positioned downstream from the burner in the flame, reduces peak temperatures and NOx. After a few iterations of testing at RIST with modeling input from Saint-Gobain, we created a NOxBuster that reduces NOx below POSCO's targets while maintaining significant energy savings.



Shortly after POSCO restarted their furnace now installed with the total burner solutions in a single zone, POSCO observed some strange behavior that required zone shutdown and further investigation. After removing the burners, they discovered significant soot deposits on the NOxBusters in multiple radiant tubes.

Saint-Gobain's R&D teams reproduced POSCO's conditions using our own pilot furnace in Paris and conducted a series of tests and simulations to determine the root cause and develop a viable solution.

Together, POSCO and Saint-Gobain learned that managing NOxBuster position during installation is very important to prevent soot formation, and we obtained a good solution that simplified installation and had little to no impact on furnace operations.