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RESEARCH ARTICLE

Energy Efficiency Enhancement and Pollution Mitigation in Dual-Fuel Fired Industrial Furnaces through Waste Heat Recovery and Robust Design

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Abstract: Atmospheric Air Pollution & Global Warming due to the emission of flue gases in the atmosphere is a major issue that is being faced by the world at present. This is due to the incomplete combustion of fuel, producing unwanted components in the flue gases, which are affecting our environment as well as nature badly day by day. It is extremely important to control pollution as well as global warming to preserve nature. This research paper has tried to discuss the cause of the exit of hot flue gases to the atmosphere and recovery of the same by controlling the exit of hot flue gases to the atmosphere. This can be controlled by the complete combustion of fuel as well as by converting the heat into energy. The equipment is installed on the furnace to recover heat losses as well as complete combustion. Ideally, industrial furnace efficiency is considered to be 30 percent for design calculations, which indicates that almost 70 percent of energy is being wasted. The combustion system is designed to achieve the required temperature with better temperature uniformity inside the combustion chamber. Automation by Auto ignition and Auto temperature control system is done for the safety and quality of the final product derived from the system. Hence, it is necessary to enhance the furnace efficiency for energy saving. This will also contribute to pollution control and global warming. An industrial furnace has a major role in the Iron and Steel Industry, Power generation, Ferrous and non-ferrous metals and alloys melting, Heat Treatment, and many more applications that consume maximum energy production globally. Hence, the energy-saving focus is required in this category. Energy-saving will not only enhance efficiency but also contribute to controlling pollution and global warming, too. Optimizing the furnace design by a robust design concept can help the end user achieve complete combustion. This will preserve nature for the next generation.

Keywords: industrial furnace, global warming, pollution control, dual-fuel, robust design

1 Introduction

Industrial furnace design is changing with the invention of new technology, computer integration with machinery & software development. The paper-based research work focuses mainly on heat losses & their recovery by installing additional equipment & automation in industrial furnaces that are used for high-temperature applications like melting, reheating, heat treatment of ferrous and non-ferrous metals, and their alloys. The focus is to design a customized furnace and automation by using the latest digital technology for measuring pressure, temperature, and volume for the most accurate and precise measurement. Manual ignition was replaced by auto-ignition for the safety of personnel. To achieve better temperature uniformity of the charged material, an auto temperature control system is used, and performance upgradation is done by a robust design principle. The efficiency of the furnace is considered 30% for design calculations globally for metal & its alloys treatment. This indicates that almost 70% of the heat is wasted. Hence, the study is mainly focused on the study of heat loss & recovering these heat losses to improve efficiency by the Robust design principle, subsequently contributing to control pollution & global warming.

Robust design is a concept of the product from the teachings of Dr. Genichi Taguchi, a Japanese quality Master. It is defined as reducing variation in a product without eliminating the cause of variation. In other words, making the product or process insensitive to variation. This variation (sometimes called noise) is classified into internal, external & and unit-to-unit variation. Internal variation is due to deterioration, such as wear of the machine, external factors relating to environmental conditions like temperature, Humidity & dust. Unit-to-unit variation is variation between parts due to variations in material, processes & equipment. An industrial furnace, an insulated enclosure called a combustion chamber in which a charge is placed & heated to raise its temperature to a required degree, which is needed for further applications like melting, reheating & heat treatment in ferrous & non-ferrous metals & their alloys in the metal industry. Applications of Industrial furnaces are in Iron & Steel, Automotive, Power Transmission Structure, Power Plants, Pipes, Casting of ferrous & non-ferrous metals & alloys, Heat treatment of metals & alloys, and so on [1–3].

There are many elements of industrial furnaces through which heat & flue gases are sent to the atmosphere, leading to global warming & pollution. If this heat is recovered by some means, then part of global warming can be controlled. Also, Flue gases contain unwanted oxides like CO (Carbon Monoxide), SO_2 (Sulphur dioxide), which can harm the natural air. Therefore, it is very important to study this subject & subsequent development to control these losses to preserve nature. The different elements that are responsible for heat losses in the industrial furnace are described as follows (Figure 1):

(1) Combustion chamber design;
(2) Control of the Combustion system or Heart of the furnace;
(3) Heat loss through Furnace Wall / Roof / Hearth;
(4) Control for Flue escape through Chimney;
(5) Heat loss through Furnace Accessories like Door, Bogie hearth, Furniture, and Structure & openings;
(6) Piping losses to carry Air, Oil, and Gas to the combustion chamber;
(7) Safety / Automation / Control system design [4].

In general, the heat energy balance equation for a furnace may be stated as follows [1]:

$$\text{Heat Input to the system} = \text{Heat utilized} + \text{Heat losses from the system} \tag{1}$$

$$QF = QC + QS + QL + QE - QR \tag{2}$$

where,
QF = Heat generated by the burning of fuel;
QR = Heat recuperated/regained from the exhaust gases;
QC = Heat utilized for heating the charge materials;
QS = Heat storage by furnace refractory & insulation;
QL = Heat loss through furnace walls, openings, ground, etc;
QE = Heat loss through exhaust gases.

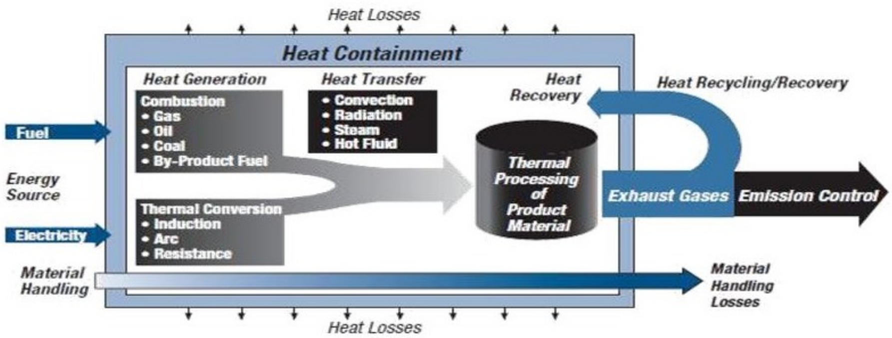

Figure 1 Heat Transfer in Industrial Furnace

1.1 Combustion chamber

The important design element & needs to be designed properly to ensure the right proportion of flue gases through the chimney. The combustion chamber is designed based on volume as the determination of furnace internal size, or in other words, the volume of the furnace, is calculated based on the following principle:

$$\begin{aligned}\text{Total Volume [V]} &= \text{Charge Volume [V1]} + \text{Combustion Volume [V2]}\\ &\quad + \text{Circulation Volume [V3]}\end{aligned} \tag{3}$$

where,
V1 = Volume occupied by the charge along with the furniture;

V2 = Space required for combustion of fuel is calculated from the maximum rate of fuel consumption (Thumb rule – 03 cubic feet per Gallon), which takes place during the period before reaching the highest temperature of the furnace. The value of V2 is mainly in the burner design. Highly efficient mixing of air & fuel reduces the combustion time/residence time for complete or 99% combustion & as a result, the volume required for combustion is reduced;

V3 = Space (Thumb rule – $1/3^{rd}$ of combustion volume) permits heat transfer from hot combustion gas to cold charge [5]. The load should be arranged in such a way as to have passages for combustion gases to flow & transfer heat to the load. With medium velocity burners, the velocity of combustion gases can be taken up to the Tune of 15 to 20 M/Sec. The void in the load space should be sufficient to permit the flow of gases at the above-mentioned rate. In addition to the load space, adequate space at the side & the top [below furnace roof] shall have to be kept for proper circulation of combustion gas.

1.2 Combustion system

It consists of all equipment that is required for firing inside the combustion chamber & mainly consists of burner, blower, Heating & Pumping unit, Gas train, control panel, Air/Oil/Gas line piping & their control equipment installed in the respective pipeline. The following key points are to be noted to have better adaptability for different load capacities, durability for long-standing, safety & better control for efficiency up-gradation during the process:

(1) Select the equipment for maximum load capacity with a good factor of safety of at least 1.2.

(2) Oversizing of combustion equipment, as well as furnace equipment for the furnace combustion chamber & wall, is allowed.

(3) Strictly no undersized equipment like blowers, heating & pumping units, Gas train, Fuel/Air control valves in the piping.

(4) MS pipe class for Air – A (Light) class, for Oil – B (Medium) class & for gas – C class (Heavy) needs to be used from a safety point of view [6].

(5) When hot air is used, use the ID fan for suction of exhaust with an SS impeller.

(6) The coupling drive is to be used for the ID fan for the suction of flue gases from the furnace chamber to the chimney escape to the atmosphere.

(7) When preheated air is used for combustion, use control valves with an SS flapper & shaft.

(8) Use an expansion flexible pipe to allow expansion of air in the piping in case hot preheated air is used.

(9) Blower, Heating & pumping unit, gas train foundation must be on the ground with proper foundation (Refer to the Manufacturer's catalog for installation, operation & maintenance) to avoid vibrations & damage to the parts mounted on them for better accuracy.

(10) Keep Blower, Heating & pumping unit, gas trains as close as possible to the furnace with piping in minimum bends to reduce pipe frictional losses.

Complete combustion means complete burning of fuel with CO_2 formation. Incomplete combustion forms CO in the exhaust flue gases, which are hazardous and lead to pollution in the atmosphere. The chemical reactions that occur in the burning of methane fuel are given below. Incomplete combustion leads to pollution in the atmosphere.

1.3 Heat loss through Furnace Wall / Roof / Hearth

The design of furnace wall/ Roof/Hearth with proper insulating material & thickness can lead to greater energy saving, thus avoiding unnecessary energy consumption & contributing to pollution control as well as global warming.

1.4 Flue gas exits through the chimney

Flue gases, also known as products of combustion (POC), impart heat energy to the charge, combustion chamber, Hearth, furniture, door & other openings & escape to the atmosphere via the chimney. A chimney is a duct passage provided to escape flue gases from the combustion chamber safely to the atmosphere without harm to men, machinery & material at the workplace. Energy conservation is like power generation, Eco-friendly, Fuel-saving, and cost reduction.

2 Energy Saving by Using VFD

2.1 Energy Saving by Heat Recovery from Flue Gases

Percentage of available heat = Best possible efficiency after flue loss, *i.e.* % of gross input used to heat the load and any losses other than flue losses. Hence % Gross Input = 100% ×

(Required available heat / % available heat). (Figure 2)

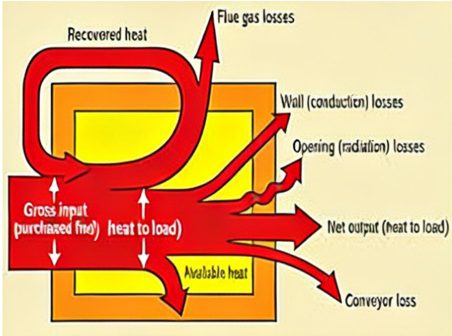

Figure 2 Sankey Diagram

A Sankey diagram is a type of flow diagram in which the width of the arrows is proportional to the flow rate used to analyze where the heat is being wasted and how to divert wasted heat to optimum use [7]. Heat recovery methods are listed as follows:

(1) Preheating cold loads – Preheating cold loads with flue gases can be accomplished in preheating chambers, in a preheat zone of a continuous furnace, or in the first part of the time cycle of a batch or shuttle furnace. Sterile Power Transmission Ltd., Silvassa (DNH-UT) has recently commissioned a Tower furnace for an aluminum melting furnace where the charge is fed from the top and flue gases are taken away from the top via the charge. The practical fuel saving by preheating the charge is about 10%.

(2) Preheating air – By using a recuperative burner or installing a recuperator in the exhaust flue path, combustion air is preheated & in turn [8], fuel is saved.

(3) Steam Generation in Waste Heat Boilers – Waste heat Boilers are mounted in the exhaust flue path and can convert much waste heat to useful free steam. Research work is in progress on whether this steam can be used to generate electricity by incorporating a steam turbine.

(4) Oxy-Fuel firing – Substituting "commercially pure oxygen" in place of air, called oxy-fuel firing. It does save energy by reducing the mass of hot waste gases thrown away through the flue. It saves fuel, improves heat transfer, and lowers NOx.

For 01 volume of methane (the principal constituent of natural gas), the combustion reaction with air is $CH_4 + 2O_2 + 7.57N_2 \rightarrow CO_2 + 2H_2O + 7.57N_2$ (10.56 Volume of flue gas), whereas with oxy-fuel firing is $CH_4 + O_2 + \rightarrow CO_2 + 2H_2O$ (only 3 volume of flue gas = 28.4% of w/air). Since there is no nitrogen in the POC (product of combustion), it helps keep NO_x formation to a minimum. The leakage of air inside the furnace needs to be avoided.

2.2 Energy-saving by using VFD (Variable Fan Drive)

Blower operates at a lower capacity than its rated capacity due to the non-customization availability of the exact HP requirement in the market. VFD automatically saves energy by lowering the speed of the motor as per the energy requirement. It is a green energy-saving product that matches the amount of work or load on a motor to the amount of energy it needs to power that amount of work. It has variable speed controls.

Example 1: If a 30 HP blower is operated at an average of 70% of its volume for 50 weeks per year. Then, how much energy is saved by using VFD?

Ans: From the fan law, Flow is proportional to RPM, but the power required is proportional to the cube of RPM [9]. Here, HP1 = 30 HP given. HP2 = HP1 $\times$ $(Q2/Q1)^3$ = 30 $(70/100)^3$ = 10.3 HP consumed by VFD. Therefore HP saved = 30 − 10.3 = 19.7 HP $\times$ 0.746 = 14.7 KW. If the power cost is \$0.05/KWH, then the savings will be 14.7 $\times$ 24 hrs. /day $\times$ 350 (50 weeks per year) $\times$ \$0.05 = \$6174.

2.2.1 Heat Losses through furnace accessories/openings

Furnace accessories like furniture in the combustion chamber for charge, door, bogie hearth consume a lot of heat during combustion & heat is also wasted through leakages/openings through walls. Hence, utmost care needs to be taken while designing these accessories & avoid leakage of heat through openings.

2.2.2 Piping losses in the Air/Oil/ Gas line

Piping losses are due to incorrect piping design in size, head, bend & frictional losses in the pipeline. Care should be taken to use the correct pipe size with good-quality material.

Unnecessary head & distance to be avoided. Minimum bends to be provided. Compressed air is used to clean through passages to remove foreign particles trapped in the pipeline. Filters to be provided at the inlet point to get clean air/fuel. Sealing with gaskets/Teflon must be done to avoid leakage throughout the piping. Pressure drop occurs due to head, bends & frictional losses. This pressure drop, in turn, makes a variation in the flow & affects the stoichiometric air/fuel ratio.

2.2.3 Safety/Automation/Control system design

Use of safety equipment, automation of furnace & flow control enhances furnace efficiency. This reduces energy consumption & controls pollution as well as global warming. It is extremely important to go for the automation of industrial furnaces for auto-ignition as well as auto-temperature control. Autoignition makes flame on/off automatically based on fuel flow. This also avoids wastage of fuel during the operation.

3 Optimization through robust design

From the narrowest to the broadest definition of combustion control, the goal is to achieve the best production output with minimum input & without any change in the system that is safe & reliable. Robust principle for Combustion control terminology without a change in any installed equipment is applied for performance up-gradation & enhancement of inefficiency to be answered with any one or combination of the following [2, 3]:

(1) Flame-safeguard control – Making sure there is a flame present while Fuel (Oil) is flowing through the burner.

(2) Auto Temperature Control – Adjusting the Firing rate to maintain the process heat.

(3) Air-fuel ratio control – Maintaining the proper burner efficiency.

(4) Process control – Adjusting multiple system components such as the burner firing rate, furnace pressure, circulation & exhaust fan rates, and product feed rates to achieve the best production results.

(5) Preheating the combustion Air for fuel saving.

All of these are important to consider for potential energy savings & reduced emissions. Collectively, they direct us to safely control combustion for effective heat generation & transfer, to maximize heat containment & to take advantage of heat recapture.

3.1 Flame safeguard control

Select the Burner that has mounting for Flame failure detector as well as the pilot for ignition. Both these functions are interlinked & monitor the burner flame throughout the operation & ensure fuel supply when the burner flame is on & cut off the fuel supply when the flame gets extinguished [10].

Procedure – Initially, a temporary fuel supply from the pilot burner mounted on the main burner is given & with the help of spark ignition, the flame is generated. Once the flame is generated, then fuel supply from the mainline starts & fuel supply from the pilot line gets off. The flame is now from the mainline fuel supply. The UV flame failure detector then monitors the flame throughout the operation. If the flame gets extinguished, then the UV flame failure detector sends a signal through the control panel to the solenoid valve provided in the mainline to cut off the fuel supply. The cycle is then repeated if the fuel supply is cut off & the furnace stops working. To cut off the fuel supply from the pilot, a solenoid valve is also provided in the pilot fuel supply line. In this way, the flame-safeguard control function is achieved. All burners fitted on the furnace have this function. (Figure 3)

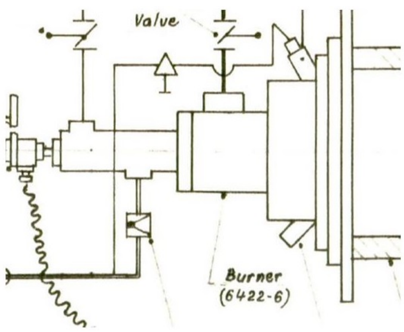

Figure 3 Auto Ignition & Flame Safeguard Control

3.2 Auto Temperature control

In an auto temperature control system, Thermocouples, i.e., for heat treatment furnaces, where the temperature requirement is more than 1000ºC, K-type thermocouple/s are used for sensing and measuring temperature. The thermocouple tip should project inside the furnace by about 100 mm from the refractory hot face. Depending upon the temperature cycle to be followed for the heat treatment process, the thermocouple may be connected to a temperature controller, On-Off/PID type, at option with programmer attached to the controller, which may operate the valve actuators to regulate the flow of fuel & air to the burners.

Thus, the flow of air, as well as oil/gas, is reduced & in turn, heat input to the furnace is on low fire. If the temperature drops below the desired level, then the valve is opened more to increase the air/fuel supply & heat input to the furnace is increased, thus turning on a high fire. This way, the valves are operated between high & low fire to control the temperature & save energy. This will reduce the emission of hot flue gases in the atmosphere to reduce pollution & global warming. (Figure 4)

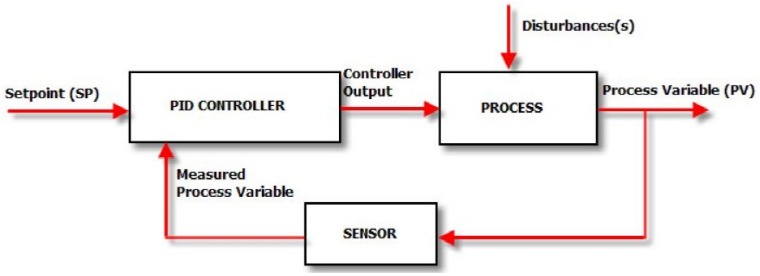

Figure 4 Block Diagram for Auto Temperature Control

A PID (Proportional Integral Derivative) controller is a device that takes the signal from the thermocouple (sensor) & modulates air/fuel supply between low & high fire in the furnace.

3.3 Fuel /Air Ratio Control

For Optimum performance, the ratio of fuel to air must be maintained at the desired level. Fuel/ Air Ration can be controlled in three different ways, as given below.

(1) Area Control – This is achieved by the use of constant pressure & variable areas. A simple mechanism can be used to cause the area of the fuel & air valves to vary in proportion to one another. This requires that the two valves with identical (or known) flow characteristics are mechanically linked to produce directly proportional movement.

(2) Pressure control – The system works on the principle of constant areas & variable pressure. Volume to control the air/fuel proportion is used.

(3) Mass Flow control – Done by controlling the mass flow.

3.4 Process control

The complete process is to be monitored & controlled by the user for heat losses from the furnace.

3.5 Preheating Combustion Air for Fuel-Saving

By using a recuperative burner or installing a recuperator in the exhaust flue path, combustion air is preheated & in turn, fuel-saving is done. (Figure 5)

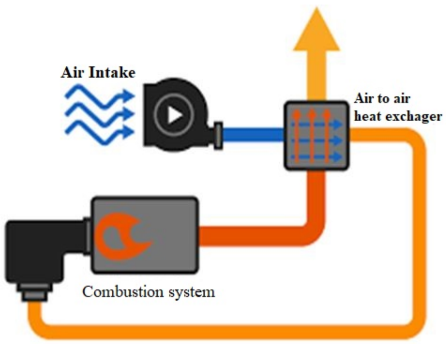

Figure 5 Heat recovery by Recuperator

Fuel-saving by preheated combustion air *vs.* flue gas temperature. (Table 1)

Table 1 Percentage of Fuel Saving

Flue Gas (°C)	Recuperated Air Preheat °C								
	300	350	400	450	500	550	600	650	700
450	12.8	14.7	16.6						
500		15.0	17.0	18.8					
550		15.5	17.4	19.3	21.1				
600			17.9	19.9	21.7	23.4			
650			18.4	20.4	22.2	24.0	25.6		
700				20.9	22.9	24.7	26.3	27.3	
750				21.5	23.4	25.3	26.9	28.2	
800				22.1	24.1	26.0	27.7	29.0	30.5
850					24.9	26.8	28.9	29.7	32.3
900						27.5	29.3	30.5	32.1
950						28.5	30.3	31.4	33.0
1000							31.2	32.3	33.9

4 Stoichiometric Air / Fuel Ratio Control

(1) Light Burner. Adjust the Regulator & limiting orifice valve as per instructions (Regulator adjusts the fuel supply through the impulse line from the air supply. The limiting orifice valve is used for micro control screw adjustment of fuel flow in conjunction with the metering orifice valve, which measures pressure.

(2) Attach a Manometer or quality air pressure gauge to the burner air connection. Set the burner air valve to the desired air pressure for Maximum firing.

(3) Open orifice holder momentarily to flush out condensate & dirt.

(4) Connect a manometer to the metering orifice valve with its equalizing valve open. Slowly open the valve to the orifice holder taps & then slowly close the equalizing valve to take care not to blow the manometer.

(5) Adjust the Limiting orifice valve for proportionate gas flow as follows: a. If the actual high fire air pressure on the gauge is 14 OSI (Ounce per square inch, American pressure unit). Then Air flow = 27000 × (14/16) = 25260 SCFH (Standard cubic feet per hour – Airflow at 16 OSI is 27000 from the burner chart).

(6) Corresponding gas flow for the above air is 2526 SCFH, stoichiometric ratio (1:10).

(7) Adjust the limiting orifice valve until the manometer across Metering orifice plate # 2400 (which allows 2400 CFH @ 3.5" WG pressure through metering orifice valve from the standard chart) shows a reading of 3.88" WG (2526/2400 × 3.5" WG). This way, High fire setting is done for a perfect Air / Fuel ratio, which saves a lot of fuel during the high fire.

(8) Turning down the fire to low fire is done by modulating airflow through a signal from the PID controller once the desired temperature is reached. Impulse line from air piping to the Air-gas ratio regulator, which operates on impulse air pressure, proportionates the gas flow.

Thus, a Low fire setting is done for a perfect Air/ Fuel ratio, which saves a lot of fuel during the minimum fire & ensures a lot of fuel-saving automatically. This way, for different loading of the charge variation in temperature, is achieved without a change in the cause of the variation according to the robust principle, without a change in any component [11]. (Figure 6)

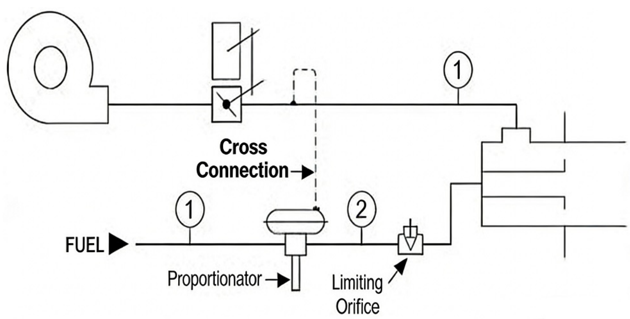

Figure 6 Auto-Air/Fuel Ratio control

5 Conclusion

This research paper deals with the heat losses & their recovery in the industrial furnace used for high-temperature applications, which is helpful for the furnace Designer, Manufacturer, as well as the end-user to run their furnace quite efficiently. Complete combustion of fuel & utilization of the heat input is required to Control Pollution, Global Warming, & Enhance Furnace Efficiency. This is with additional development with a practical observation of the furnace, existing setup & feedback from the Furnace Designer as well as the End-user. Safety is the most important factor to be considered.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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