THOR - Induction Heating of Processes

Public report

Author(s) Soraya Sluijter, Jurriaan Boon, Galina Skorikova, Gerard Elzinga, Aris Twerda (TNO), Laingyuan Wei, Tom Smetsers, Ivo Roghair, Martin van Sint Annaland (TU/e), Arjan Koekkoek, Erik Abbenhuis (Hybrid Catalysis), Guido Jasper, Frank Kuster, Eduardo Diaz Angulo (Ambrell) and Babak Farschi (Total Energies)

Classification report	TNO Public
Summary	TNO Public
Sponsor	RVO
Programme name	TIND121010
Programme number	TSE Industrie
Project name	THOR – Induction Heating of Processes
Project number	060.50522

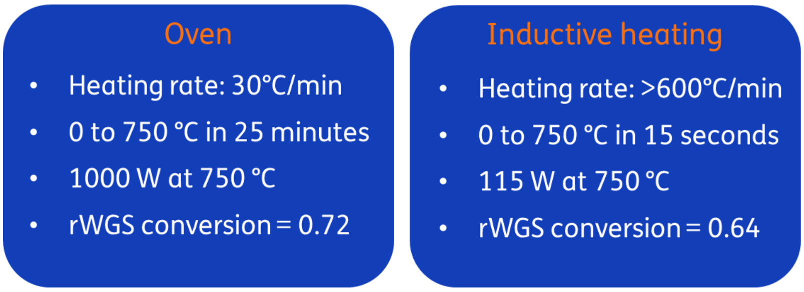
Contents

Samenvatting

Het doel van het THOR project was om verwarmingstechnologieën gebaseerd op inductie te ontwikkelen om chemische processen te elektrificeren om bij te dragen aan het halen van het Nederlandse klimaatakkoord. Het project onderzocht twee toepassingen: de productie van smeermiddelvet en katalytische processen door middel van inductieverwarming van gestructureerde interne onderdelen en directe verwarming van katalysatoren.

De directe inductieve verwarming van vaten voor smeermiddelproductie door middel van spoelen is onderzocht en zowel efficiënt als veiliger dan het huidige proces beoordeeld. Hoewel de benodigde retrofit initiële kosten met zich meebrengt, kan het tegen 2050 de koolstofvoetafdruk aanzienlijk verminderen, mogelijk tot 75%. Onmiddellijke integratie van onsite hernieuwbare energiebronnen zoals zonnepanelen of windparken is nodig voor de beperking van emissies. Dit concept wordt verder ontwikkeld en getest op pilot- en demonstratieschaal door Total en Ambrell.

Inductieve verwarming van katalysatoren richtte zich op een belangrijke koolstofgebruiksreactie, de omgekeerde water-gas shift (rWGS) reactie. Uit de geteste katalysatoren kwam een cesium-gepromote ijzer/koperkatalysator naar voren als de meest veelbelovende. Er zijn pogingen gedaan om deze katalysatoren rechtstreeks met inductie te verwarmen, maar vanwege de beperkingen gerelateerd aan o.a. de deeltjesgrootte verschoof de focus naar gestructureerde interne onderdelen. Hoewel rechtstreekse verwarming van de katalysator mogelijk was, vereiste dit meer energie en kampte het met afschermingsproblemen. Gestructureerde interne onderdelen bleken efficiënter. IJzeren ringen bleken efficiënte elementen voor inductieve verwarming. Testen in de rWGS-reactie toonden een ordegrootte hogere efficiëntie aan voor inductieverwarming in vergelijking met conventionele ovenverwarming met niet-geoptimaliseerde systemen. Inductief verwarmen leidde tot vergelijkbare conversies in vergelijking met conventionele ovens met een veel lager elektrisch vermogen. Bij hogere temperaturen werden echter warmteoverdrachtsbeperkingen tussen de ijzeren ringen en de katalysator waargenomen, wat wijst op het belang van geoptimaliseerde driedimensionale structuren voor efficiënte inductieve verwarming.



Modellen zijn ontwikkeld om inductieverwarming te bestuderen en de gestructureerde interne onderdelen te optimaliseren. Echter, de verschillende simulatiemethoden toonden discrepanties in het simuleren van inductieverwarmingseffecten. ANSYS-simulaties sloten beter aan bij experimentele gegevens en gaven aan dat gesloten kringen nodig zijn om de verwarmings-efficiëntie te verbeteren. Verschillende open onderzoeksvragen blijven bestaan, zoals het begrijpen van de impact van materiaaleigenschappen op de efficiëntie van inductieverwarming en het opnemen van temperatuurafhankelijkheden in de simulaties.

Inductieverwarming toont potentieel voor reactieve processen (bij hoge temperatuur) in de chemische industrie. Een SWOT-analyse identificeert gestructureerde interne onderdelen als de meest veelbelovende toepassing voor inductieverwarming. De routekaart schetst toekomstige ontwikkelings- en toepassingsmogelijkheden, waarbij de transformerende potentie van inductieverwarming voor verschillende industrieën wordt benadrukt

1 Project information

Project titel	THOR - Induction Heating of Processes
Project number	TIND121010
Coordinator	TNO
Project period	01/01/2022 - 30/10/2023
RVO Program line	MMIP 8 – Maximale elektrificatie en radicaal vernieuwde processen

This work has received funding from Topsector Energie of the Ministry of Economic Affairs and Climate Policy (TIND121010).

Project partners:

Organisation	Location	Main contact	e-mail
TNO (coordinator)	Petten	Soraya Sluijter	Soraya.sluijter@tno.nl
University of Eindhoven (TU/e)	Eindhoven	Martin van Sint Annaland	M.v.SintAnnaland@tue.nl
Hybrid Catalysis	Eindhoven	Erik Abbenhuis	H.C.L.Abbenhuis@tue.nl
Ambrell	Hengelo	Guido Jasper	Gjasper@ambrell.com
Total Energies	Beverwijk	Babak Farshchi	Babak.farshchi@totalenergies.com

2 Background and objectives of the project

2.1 Introduction

The Dutch climate agreement has identified the electrification of the chemical industry as an important element to become climate neutral. Inductive heating (figure 1) is a way to achieve this based on alternating electromagnetic field, modes of heating:

- Superparamagnetic: Néel relaxation losses in nanoparticles (e.g., FeOx < 20 nm) > medical applications hyperthermia treatment, organic syntheses
- Hysteresis losses in ferromagnetic materials: magnetic dipoles continuously oscillate, friction causes heating
- Eddy currents (Joule heating): magnetic field creates an electric current, heating by electric resistance.

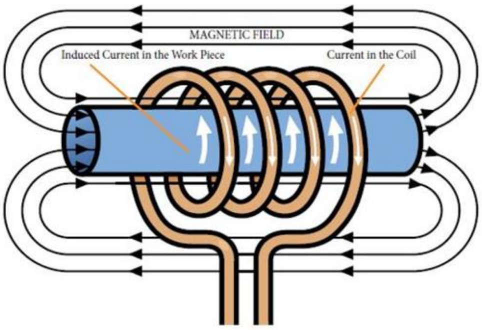


Figure 1: Schematic representation of Inductive heating.

It offers many advantages such as a high heating rate, energy efficiency, the possibility to provide heat in-situ and enhanced heat transfer, while being easy to implement and safe in operation. However, induction heating applied to chemical processes is still in early stages. In the THOR project, approaches to electrify catalytic processes have been investigated: 1. inductive heating of structured internals (WP2) and 2. direct heating of catalysts (WP3). For the former, catalytic reactor technology for reverse water-gas shift (CO_2 conversion) will be re-engineered for heat management in the reactor, to make optimal use of the advantages of inductive heating while relying on proven catalyst technology. This represents an ambitious step forward in applying inductive heating, yet allows implementation in the short term. For the latter, taking the reactor modifications yet another step further, existing reverse water-gas shift catalysts will be redesigned to enable direct inductive heating. This represents the highest benefit from a process point of view, allowing for minimal temperature gradients, maximum heat transfer rates, and good controllability. This report describes the experimental work performed at TNO for the two approaches.

Contributing directly to the industrial electrification and development of radically renewed processes, the THOR project provides a benchmark for the inductive heating of chemical processes.

2.2 Project objectives

The objective of THOR is the development of induction heated processes for the process industry. On three different levels, the potential of inductive heating was investigated through a close combination of theoretical modelling and experimental validation. In order to further advance induction heating into a disruptive innovation leading to radically new processes, THOR took a three-way approach: (1) vessel heating, (2) structured reactor internals, and (3) direct heating of catalytically active materials. Three objectives were accordingly defined: 1. Establishing the technical and economic feasibility of replacing natural gas-fired heating systems with thermal oil by inductive heaters, and prepare pilot demonstration. 2. Establishing the technical and economic feasibility of using structured internals for inductive heating in the heat-demanding reverse water-gas shift reaction. 3. Establishing the technical and economic feasibility of direct catalyst heating by induction in the heat-demanding reverse water-gas shift reaction.

3 Methods & results

3.1 Method

In three work packages that build onto each other, the three levels of inductive heating were developed. TotalEnergies, Ambrell, and TNO established (1) the technical feasibility for rapidly deployment of inductive heating of lubricant grease production vessels. TNO, Hybrid Catalysis, Ambrell, and TU/e then investigated (2) the inductive heating of structured internals and (3) direct heating of catalysts, both for the reverse water-gas shift reaction. Experimental proof-of-concept was delivered using materials developed by Hybrid Catalysis at the facilities of TNO and TU/e using Ambrell inductive heating equipment. Modelling by TU/e and TNO would allow for reactor design and optimisation. An implementation plan (roadmap) was made that addresses the technical, economic, commercial, organizational, and political/societal aspects with specific attention to the impact on CO_2 emissions and intermittency of electricity supply.

3.2 Results

WP1: Inductive Vessel heating

The objective of WP1 was to establish the technical and economic feasibility of replacing natural gas-fired heating systems with thermal oil by inductive heaters, specifically for the lubricant grease production of Technip Energies in Beverwijk.

Following the ambition of Total Energies to significantly reduce their carbon footprint while not compromising the fabrication procedure, different technical options for inductive heating of the vessels were evaluated with respect to energy consumption, safety of the process, noise level, easiness of retrofitting, timeline of implementation, and associated costs. Direct inductive heating of the wall of the vessel using an inductive coil was found to be the most attractive option in terms of carbon footprint reduction (figure 2). Furthermore, the removal of thermal oil will improve the safety of the plant. It is possible to retrofit existing vessels from using thermal oil to direct induction relatively easily.

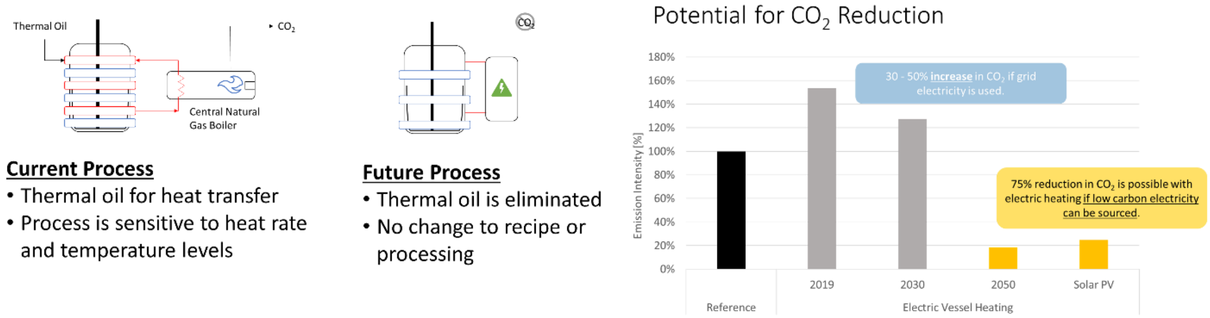


Figure 2: Comparison of current and future process and CO_2 reduction potential.

Based on the calculations, electrification of the facilities is foreseen to reduce carbon footprint of the production site by up to 75% by 2050 considering the projected emissions intensity of the electrical grid of31 gCO_2/kWh in the Netherlands. However, considering current electricity prices in the Netherlands, such a retrofit does not show a positive business case (20 years payback time). However, the sustainability target can be achieved earlier when the production site installs renewable energy sources onsite to fully supply the power to the facilities. Installation of PV panels or a wind park on short term on site will significantly speed up CO_2 emissions reductions and increase annual savings associated with electricity costs and CO_2 taxes.

Ambrell and Total Energies are in the process of scaling up this technology further.

WP2 & WP3 Inductive heating of catalytic processes

Model benchmark and validation

The objective was to model the heat transfer and chemical reactions in the bed as a function of the shape and placement of the reactor internals in order to arrive at high heating rates, optimal heating efficiencies, and minimal temperature gradients. To this end, two OpenFOAM solvers were developed and applied in 3D simulations for magnetic field and induced power solving at TU/e and a model using the ANYS software environment has been built at TNO. The latter model couples the ANSYS-Maxwell solver (Magnetic field and induced power) with the ANSYS Fluent solver (Heat transfer and Fluid flow). Both models, OpenFOAM and ANSYS, were quantitively compared with each other and also qualitatively with experiments performed at TNO and TU/e.

For simple workpieces the models led to very similar results. However, when adding work pieces to the model, the results from the models start to deviate unfortunately. When comparing the results of the simulation with experiments performed at TNO and the TU/e it can be observed that, qualitatively, the results generated with ANSYS software are much more in line with the experiments than the results generated with using the OpenFOAM software. This is depicted in Figure 4 where on the top row simulation results are plotted and on the bottom rows (thermal) pictures from experiments are shown. From these pictures it can be seen is that the induced current, hence heat generation, is taking a closed path on the outer most part of the centre piece. This effect can also be clearly observed in the ANSYS simulation but not the OpenFOAM ones. The reason for the differences of the simulation is not clear for now. Most possible explanations are that 1) the skin-depth is not accurately resolved in the OpenFOAM set-up or 2) that the equations solved inside the OpenFOAM solver are not able to simulate this effect properly. More research will be required to make a definite answer on the origin of these differences.

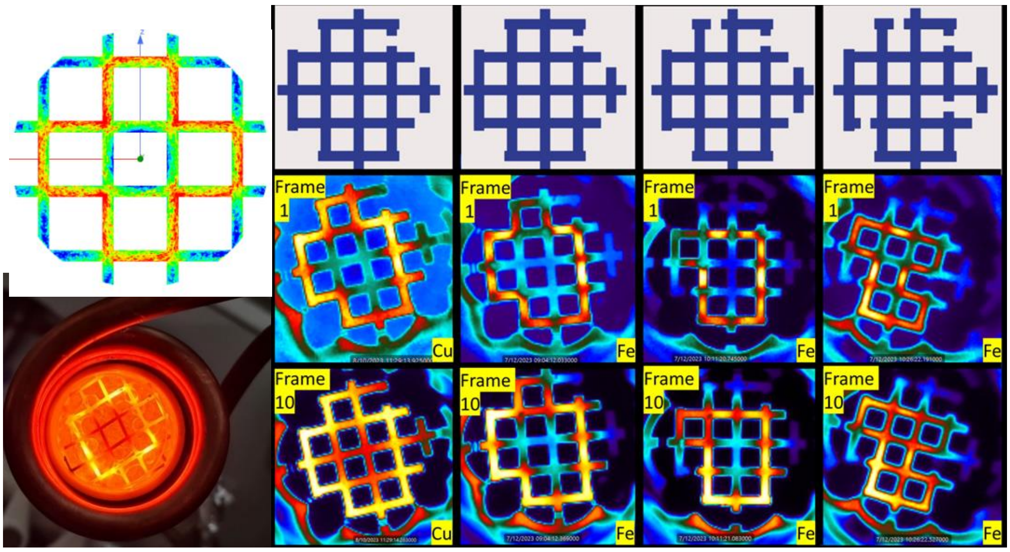


Figure 3: Qualitative comparison of experiments and simulations. Top row are simulations: Most left one is from ANSYS, the right four are openFOAM. Bottom row are experiments: Most left from TNO, the right four from TU/e.

From the validated ANSYS model it can be concluded, that closed circle are required to allow for eddy currents and thus more efficient heating in the structure. As expected, closer to the spools higher induction was observed (proximity effect). It proved to be more challenging than anticipated to model the IH beds, as became apparent form the different results from the models. The ANSYS models can be used to optimize the design of internals in follow-up projects.

Aside from the different results between OpenFOAM and ANSYS there are still some more open research questions in the modelling work. Firstly, the influence of the EM (electro-magnetic) material properties on the efficiency of inductive heating is not totally clear yet. To be able to optimize the process geometries this information will be required. Secondly, the temperature dependency of these properties is also not included in the simulations yet. It is expected that this will change the outcome of the models, though more quantitively than qualitatively. In the current model the centre piece is heated up indefinitely. However, in reality the change in EM properties will result in a lower induced current and hence a lower heat source. Furthermore, above the Curie temperature the induced current will definitely change. These effect have to be implemented and investigated.

Catalyst synthesis RWGS

At the start of the Thor project Hybrid Catalysis made a literature search of possible RWGS catalysts for the project. From all possible catalysts a group of three candidates was selected being viable considering reported conversion, materials availability, and overall catalyst costs. The selected catalysts are listed in the fout! verwijzingsbron niet gevonden. below.

Table 1: RWGS catalysts overview

entry	active metal	promotor	support	loading	promotor loading	catalyst	max CO_2 conversion (literature)	price / kg
1	Ni, Co		CeO_2 $Ce_{0.75}Zr_{0.25}O_2$	0.5-2%		**(0.5%) Ni/$Ce_{0.75}Zr_{0.25}O_2$**	**62.50%**	€€€
2	Fe	Co Cs Cu	Al_2O_3	13.50%	1.50% 5-10% 10-15%	**(4.5%) Cs–(10%) Cu–(15%) Fe–Al_2O_3**	**62%**	**€**
3	Cu	Ru	ZnO/Al_2O_3 CeO_2	5.6-40%	0.50%	**(0.5%)Ru–(40%)Cu /ZnO/Al_2O_3**	**46%**	**€€**

All candidates were first synthesized at small scale directly followed by 100-gram scale synthesis. Each catalyst was tested in our conventional setup under conventional RWGS conditions (1/2" o.d. reactor; 1 g cat + 1 g SiC; 375 mln/min; 12 H_2 : 2 CO_2 : 1 Ar) to validate the activity of the prepared materials. fout! verwijzingsbron niet gevonden. below gives the total CO_2 conversion for each catalyst at different temperatures.

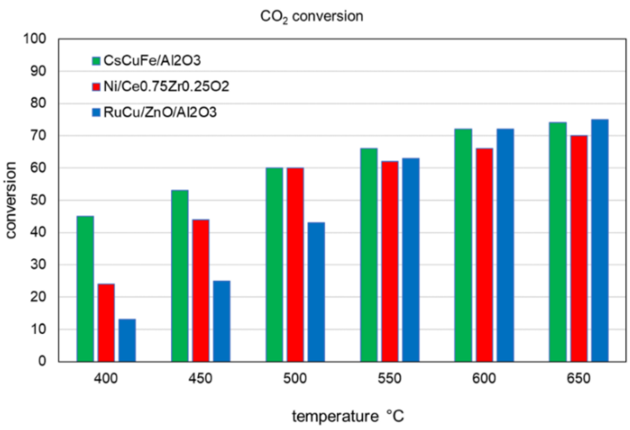


Figure 4: CO_2 conversion for the three selected catalysts measured on a conventional reactor.

For all three catalysts a small test batch was shipped to the relevant partners. From the initial tests the cesium promoted iron/copper catalyst was selected as the most promising candidate for the RWGS reaction in the THOR project. This catalyst was tested under different reaction conditions. Figure 6 gives an indication of the effect of space velocity, temperature and feed ratios on the CO_2 conversion. Note that during the testing no significant amount of methane was formed showing the strong preference of the RWGS reaction over the methanation reactor for this catalyst. A duration test using the catalyst showed stable operation for almost 100 hours' time on stream. With roughly 0.5 gram carbonaceous deposit form per gram of catalyst over 100 hours. The selected catalytic material have been shipped to TNO and TU/e for testing in their induction heated setup.

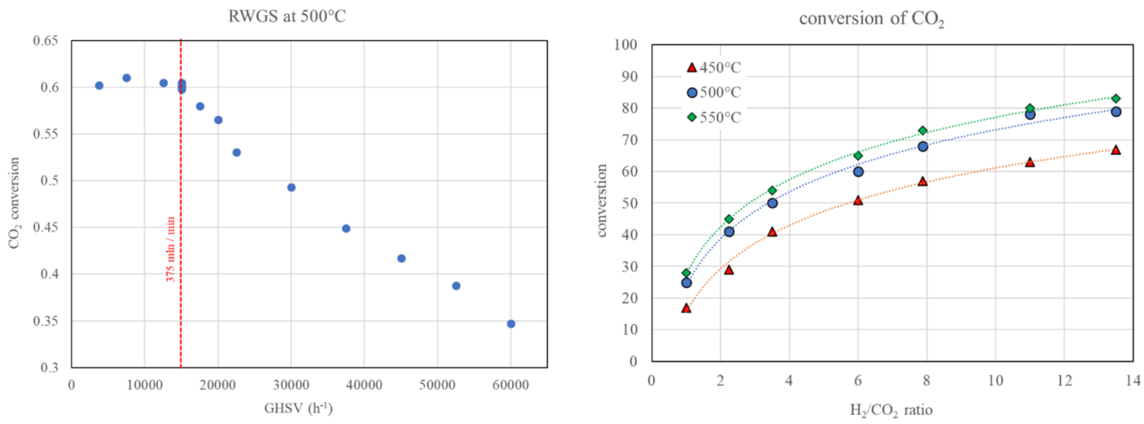


Figure 5: Effect of the GHSV on the conversion (left) and effect of temperature and feed ratio (right).

Direct catalyst heating vs structured internals

The RWGS catalyst as well as physical mixtures of inert material or the catalyst with e.g. Iron particles have been tested for their induction heating capabilities. The materials could be heated inductively, depending on the particle size. However, a lower maximum temperature was reached and/or higher power input was required for direct catalyst heating compared to the structured materials (same wt% of susceptible material), see fout! verwijzingsbron niet gevonden. As this approach seemed to be more efficient, more effort was put into structured internals in the remainder of the project. Direct catalyst heating using magnetic particles coated with catalyst may be of interest, but these have the drawback of more complex (and expensive) synthesis, less active material and lower applicability compared to the structured internals.

Table 2: High level overview of efficiency of IH for several materials and shapes and sizes.

Material	Shape/size	Heating
Iron	Grid	
Galvanized iron	Grid	
SS 316 & SS304	Grid	
Galvanized iron	Grid wave (1)	
Galvanized iron	Grid cylinder (2)	
Iron particles	6-8 µm	
Iron particles	150-300 µm	
Iron particles	1000-2000 µm	

Proof of concept: Inductively heated RWGS using structured internals

At the start of the project grids made of different materials were studied, but not quantified. A high level overview of the results is depicted in Table 2. Glass fibre sensors were incorporated in the TNO set-up to measure the temperature over the bed, which led to a patent on controlling the temperature in specific parts of the bed.

To quantify the heating of the structured internals a method for the determination of the specific absorption rate (SAR) as a function of temperature was developed at TU/e. This method estimates a heat transfer coefficient as a function of temperature extrapolated over multiple measurements. The experimental work involved the use of a custom-built induction heating system to study the heating of workpieces combined with a thermographic camera. From the workpieces studied (disk, mesh and rings, without prior consideration on optimizations), the rings proved to be most efficient and were used for testing in the RWGS reaction and compared to a conventional oven. The induction heater used approximately 115 W to perform the reaction at the maximum temperatures measured of 750 °C, this is nine times less compared to the induction oven.

The main goal of the project was to experimentally determine if induction heating is a viable method to perform the RWGS reaction. The Iron rings were used as heat sources in the RWGS reaction for comparison with conventional heating at TU/e. The experiments showed that at temperatures below 400 °C the induction heater had a higher conversion compared to the oven (Figure 11, left). At temperatures above 400 °C the conversion in the oven was higher. A probable cause for this is that there are heat transfer limitations from the iron rings to the catalysts. This is supported by the results for the experiments with at different flows, ranging from a weight hourly space velocity (WHSV) of 6.250, to 25000 mL/g/min (Figure 11, right). Indeed a temperature difference of over 100 °C was observed in separate measurements. Indicating that optimised (3D structured) internals are required for efficient and even inductive heating.

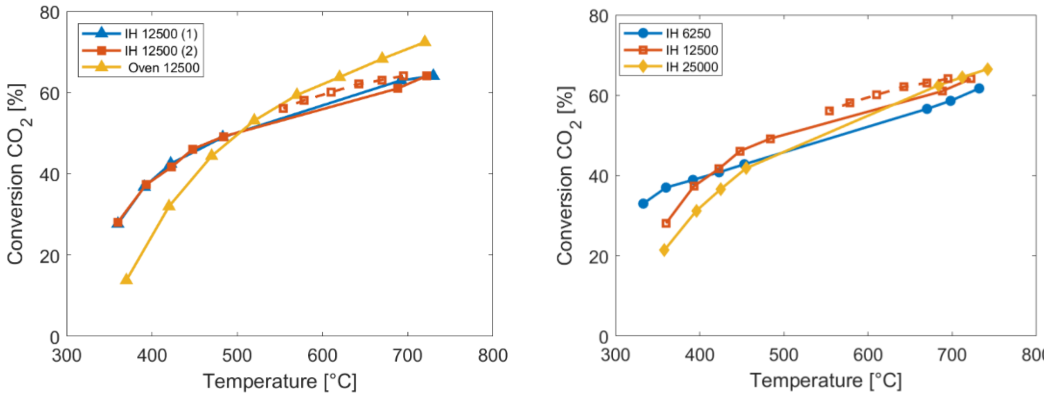


Figure 6: Left: RWGS conversion inductive heating versus conventional oven heating at various temperatures. Right: Inductively heated RWGS at varios weight hourly space velocity (WHSV).

Preliminary tests were done with 3D structured internals at TNO. Also here it was found that closed circuits e.g. the cylindrical shape is beneficial (Table 2). This structure showed the fasted heating rate and lowest power requirements for heating. This 3D structured internal was also applied for heating in the RWGS reaction. RWGS activity was confirmed at ~380 °C for 50 hours. The glass fibers confirmed that the temperature was more evenly distributed over the bed compared to using the two rings. However, side reactions were also observed: disproportionation into carbon (Boudouard reaction) and methane formation (Sabatier reaction). Post analysis showed that the structured internal material contained trace Copper that catalyses methanation.

Roadmap inductive heating of processes

Induction heating is a transformative technology that offers high efficiency, precision, and fast heating capabilities to conductive materials of various shapes and sized. The technology is widely used in different industries, including metal heat treatment, food processing, welding, and soldering. Induction heating has the competitive advantage over other electric heating options by allowing for localized, no-contact and controlled heating, this way, it ensures clean, efficient and controllable operations (figure 7).

The technical, economic, commercial, organizational, and political/societal aspects of inductive heating of processes for vessel heating and reverse water-gas shift were considered with the project team over several workshops, as well as the outlook towards possible alternative applications. The best application of IH was defined as being high temperature, endothermic, (intermittent) reactive processes in chemical industry i.e. RWGS, (ammonia) cracking, reforming and gasification. A SWOT analysis was performed for the different WPs (figure 8 shows that for the most promising option of structured internals) and the roadmap for further development and application of IH of processes was developed. Follow-up opportunities and potential collaborators and competitor were identified.

Pros		Cons
Rapid, homogeneous and efficient	**Dielectric: Microwave radio frequency**	Careful control of heating required; may require shielding; limited to dielectric materials
Fast and efficient; high precision; low costs; simple maintenance; easy integration in the infrastructure	**Infrared**	For flat surfaces, complex equipment positioning; high investments
Fast-to-immediate response (speed) due to high heat transfer rate; efficient; high precision; suitable for any shape	**Induction**	Specific material requirement
Simple; efficient; great control; low maintenance	**Resistive**	Limited heat transfer coefficient (speed)
Fast response (speed); minor modifications to existing equipment	**Plasma**	Low precision; limited heat transfer coefficient (speed); complex recycle of the carrier gas with a heat exchanger
Simple; efficient; good control	**Electric arc**	Limited heat transfer coefficient (speed)

Figure 7: The advantages and disadvantages of electric heating technologies.

Figure 8: SWOT analysis RWGS with structured internals.

4 Bottlenecks and follow-up

4.1 Bottlenecks

During the project some challenges were encountered which are described below. Despite these challenges the THOR project has achieved the main deliverables and goals.

Technical challenges

The following technical and scientific issues were encountered during the project:

- Modelling complexities exceeded initial expectations, resulting in discrepancies between the results obtained from TU/e and TNO.
- The use of structured internal materials containing impurities beyond pure iron led to unexpected methanation side reactions.
- Direct catalyst heating posed greater difficulties and proved less efficient than originally anticipated, posing a challenge for implementation.

Operational challenges

The following operational issues were encountered during the project:

- The complexities faced in modelling (as mentioned above) impacted the project's timeline, an extension of 6 months was approved by RVO.

4.2 Follow-up of the THOR project.

The THOR project showcased the potential of induction heating for the chemical industry, particularly in the context of electrifying processes to achieve climate neutrality. Induction heating is not only beneficial for reducing CO_2 emissions, it also offers safety advantages, which was evident from the investigation on inductive vessel heating. Additionally, its potential lies in delivering tailored, localized heating solutions for various processes.

Following the promising results in WP1 on vessel heating, Total Energies and Ambrel have been scaling up the selected approach in the plant in Beverwijk.

Particularly, the structured internals approach was shown to be a promising approach to inductively heat catalysts for the RWGS reaction. In the project an order of magnitude higher efficiency for inductive heating compared to conventional oven heating using unoptimized systems was measured. However, at high temperatures (>400 °C) heat limitations seem to decrease the conversion. Therefore, it is recommended the development and optimisation of 3D-structured internals is recommended for induction heating in catalytic processes. At TU/e a student is working on reactor design and a more elaborate techno-economic assessment until the end of January 2024.

Furthermore, the consortium is in the progress of setting up a follow-up project of THOR going to higher TRL levels for RWGS as well as for other applications. A Horizon Europe proposal has already been submitted on inductive heating of dry reforming.

5 Contribution to objectives of the program

The Dutch industry plays an important role in economy and society while at the same time, it is responsible for ~40% of greenhouse gas emissions. In the Climate Act on May 28, 2019, the Dutch government has set ambitious targets to reduce the Netherlands' greenhouse gas emissions (compared to 1990 levels) with 49% by 2030 and 95% by 2050 . Subsequently in the National Climate Agreement, agreements were made with the sectors including industry on achieving these climate goals. The transformation to a sustainable and inclusive industry will enable it to continue providing prosperity and contributing to the quality of life, employment and the competitive position of the Netherlands.

Targets set for 2050 include complete climate neutrality and maximum electrification. Since renewable energy largely becomes available as electricity, industrial processes should directly use electricity as much as possible. Additional aspects to address include system integration and flexibility. This is currently being addressed in **MMIP 8**: Electrification and radically renewed processes: the development of electrically driven processes enhances the uptake of renewable electricity by the chemical industry. The THOR advanced the inductive heating of processes: a challenging but very promising method of electrification.

The Reverse water-gas shift (RWGS) reaction, either conventionally or separation enhanced, converts CO_2 into syngas and requires a significant amount of heat, while it is the predominant route for CO_2 conversion into synthetic liquid fuels . Thus, the THOR project has also contributed to the circular CO_2 ambitions laid down in **MMIP6** with the electrification of RWGS.

6 Dissemination

At the start and the end of the project a newsflash of the THOR project was launched on LinkedIn.

The THOR results were presented at the NPS 2023 conference in Twente (2 poster presentations).

A review paper was prepared by TU/e and TNO, that will be submitted soon for publication. Other peer-reviewed publications are pending due to the high IP potential of the findings in the THOR project. During the course of the project one TNO patent was published already and two more are in preparation.

7 Signatures

Petten

ValidSigned by Rita Almeida
on 2024-04-11 17:03:02

A.R. Almeida
Deputy Research manager

TNO

ValidSigned by Soraya Sluijter
on 2024-04-11 10:54:09

S. N. Sluijter
Author/ Project manager