Applied Thermal Engineering 78 (2015) 387–396

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Simulation model for the transient process behaviour of solar aluminium recycling in a rotary kiln

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HIGHLIGHTS

- Transient model of solar aluminium recycling plant has been developed and validated.
- Transient behaviour of a solar rotary kiln smelting furnace has been simulated.
- A case study for a stand-alone plant operated at El Paso, Texas was performed.
- Simulation provided an overall plant efficiency of 52%.
- A maximum daily efficiency of 72% was found if solar conditions are very good.

ARTICLE INFO

Article history:
Received 17 July 2014
Accepted 3 January 2015
Available online 12 January 2015

Keywords:
Aluminium
Melting
Recycling
Solar
Rotary kiln

ABSTRACT

The German Aerospace Center has developed a process concept for the solar thermal recycling of solid residues and waste materials in a commercial scale and applied this concept to the production of secondary aluminium. In this context a mathematical model for the simulation of the unsteady-state behaviour of a solar heated rotary kiln has been developed, which is used to figure out the specifics of the solar boundary conditions like intermittent insolation and at least one start-up period per day as well as for process design purposes. This model is also capable to simulate hybrid and conventionally fossil heated processes in rotary kilns.

The model was adapted and validated by recycling experiments using a rotary kiln in mini-plant scale heated by a solar furnace. Subsequent experimental results were in good agreement with the data predicted by the transient calculations. Taking this as a basis the model was applied to predict a possible operation concept for a stand-alone plant operated solar-only at El Paso, Texas. An important step for further design studies was the calculation of the overall efficiency and the number of cycles feasible at representative days in such a plant. In a representative parameter studies the influence of geometrical kiln parameters on the efficiency and cycle duration of the batch process was investigated.

1. Introduction

The combustion of fossil fuels can be substituted by the application of concentrated solar radiation not only in power generation but also in chemical and metallurgical high temperature processes. The feasibility of solar power generation in a technical scale using central receiver systems for solar radiation has already been shown [1]. Similar plant concepts are generally suitable also for furnace based processes like the high temperature treatment of low calorific materials and metals. In this case a furnace is used as radiation absorber and at the same time as reactor for the high temperature process. One important high temperature application is the recycling of aluminium, which delivers secondary aluminium, a strongly demanded product with a still growing market due to its use in the packing, the construction and especially the automotive industry.

One important reactor type, widely used in industrial aluminium recycling plants is the rotary kiln having high flexibility towards throughput and towards the kind and the metal content of the scrap. In conventionally heated kilns a natural gas–air or a natural gas–oxygen burner is mounted in the front door closing the reactor during the heating period. Even if the technology is in

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http://dx.doi.org/10.1016/j.applthermaleng.2015.01.007
1359-4311/

Nomenclature

A	area, m^2
c	heat capacity, kJ/(kg K)
c_p	specific heat capacity, kJ/(kg K)
d	diameter, m
F_{ij}	form factor, –
H	enthalpy, J
$\dot{H}$	enthalpy flow, J/s
h	mass specific enthalpy, J/kg
h	Planck constant, J s
L	length, m
m	mass, kg
$\dot{m}$	mass flow, kg/s
$\dot{Q}$	heat flow, J/s
$\dot{q}$	heat flow density, J/(m^2 s)
r	radius, m
T	temperature, K
t	time, s
V	volume, m^3

Greek symbols

ΔT	time length, min
α	heat transfer coefficient, W/(m^2 K)
ε	emission ratio, –
η_v	efficiency, –
λ	heat conductivity, W/(m K)
ρ	density, kg/m^3
ρ	reflection ratio, –
σ	Stefan–Boltzmann-constant, W/(m^2 K^4)
Φ	filling ratio, –
ϕ	form factor, –
Ψ	quell term, –
ψ	filling angle, rad
ω	angular velocity, s^{-1}

Subscripts

Al	aluminium
b	beginning
bO	back opening
$conv$	convection
e	ending
fO	front opening
G	gas
i	inside
out	out coming
rd	radiation
S	salt
sol	solar
tot	total
uW	unwetted wall
v	losses
W	wall
wW	wetted wall
X	general index for W, G, Al and S

general established for many applications since several decades recent development address different new aspects to improve process performance related to heat transfer [2,3], energy consumption [4,5], energy balance [6–8], material flow [9,10], mixing effects [11], flue gas treatment [12,13] etc. For solar operation of a rotary kiln an open aperture or a transparent window for introducing the radiation is needed [14–16].

Regarding solar application a rotary kiln has been proven to be a suitable unit for use as a direct absorbing receiver reactor to provide high temperature process heat [17]. In the 500 kW scale tests at the solar furnace in Odeillo, France, temperature levels up to 940 °C were achieved when heating sand as the heat carrier medium. Beyond that rotary kilns are rather universal tools in high temperature processes. Thus the results of the technology development in solar thermal recycling of aluminium may be diversified and transferred to processes like pyrolysis, detoxification of filter residues, metal containing dust and foundry sands, as well as the production of iron oxide based pigments and the production of cement or lime. Alonso and Romero give a comprehensive overview on the options in terms of coupling solar radiation to the different applications [18]. For example Meier et al. reported on the application of a rotary kiln for solar lime productions, its experimental proof by testing it in a solar furnace set-up [19–21] and by evaluating the economic potential [22]. Roeb et al. analysed the use of a rotary kiln for solar treatment of industrial residues and wastes [23], Navarro et al. did such analysis for wastes from mining [24]. Yilmazoglu et al. [25] analysed a solar assisted rotary coal dryer in terms of exergy, economy and environment. Bathen et al. compared different receiver and furnace technologies for solar aluminium melting and recycling [26]. Ahmad et al. even extended such concepts towards much higher temperatures allowing the melting of glass [27]. Neises, Tescari et al. investigated the use of a solar heated rotary kiln for metal oxide reduction experimentally [28] and by numerical simulation [29,30].

To pave the path for a push of a solar technology for aluminium recycling into the market the following items have to be done: demonstration of technical feasibility in laboratory and pilot scale, concepts for industrial realisation of the technologies, assured predictions about feasibility in industrial scale, market and economic analysis as well as system integration.

An important instrument for the preparation and backing of the step from a mini-plant operation to the start-up of a pilot or even commercial sized plant is the use of simulation models. Compared to fossil or electrically heated kilns the solar heating of a kiln will bring about exceptional and uncommon operation conditions due to alternating insolation, which requires at least one start-up and one shut-down period per day. Beyond that the operation of the plant is batchwise. Therefore a mathematical model is necessary which allows to investigate the transient thermal behaviour of the process and to support the design of solar heated rotary kilns. The set-up, test, and application of such a model were task and objective of our investigations which are described in the following.

2. Process and plant

The classical remelting process for secondary aluminium production includes the melting of contaminated aluminium scrap in a conventionally fossil heated rotary kiln. The tasks of the kiln are melting and conditioning of the scrap and at the same time phase separation. For that purpose the kiln is being rotated and the scrap in the kiln is covered by a salt flux which typically is a mixture of NaCl, KCl and CaF_2. The flux has three main functions: a) prevention of oxidation of the molten aluminium by atmospheric oxygen which is sucked trough the kiln, b) support of the phase separation of