A CRITICAL REVIEW OF C_P CALCULATIONS WITHIN THE FLUIDIZED BED OF CEMENT ROTARY KILNS

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ABSTRACT

The cement industry is one of the most energy-intensive industries, as the production of cement requires high temperatures for the activation of sintering reactions inside the rotary kiln[1]. Thermal energy makes up around 80% of primary energy consumption (burning process of raw materials), while electrical energy the remaining 20%[2]. Currently, the average energy consumption in more advanced kilns, depending on the kiln type, is approximately 3.5 GJ per ton clinker produced[3] a number that has improved due to upgrades that have been made over the years in rotary kiln design and operation. In order to optimize the kiln operation it is important to study different parameters that can improve the energy efficiency and preserve the final product quality. One of those parameters is the specific heat capacity of the fluidized bed which is a thermodynamic property that depends on temperature (and/or composition) and which is expected to be variable considering that the temperature range inside the kiln varies from 800 K to nearly 2200 K. However, according to most reported studies, the C_p of the bed is considered constant along the kiln[4]. In the current study we examine the validity of the aforementioned assumption. For the current calculations, a mixing rule reported in literature was applied in order to calculate the C_p of the fluidized bed utilizing temperature and composition profiles reported in the literature. An in-house code was developed for the comparison of the literature-reported C_p's and those resulting from the mixing rule. It was discovered that the C_p of the fluidized bed had a proportional increase with the increase of the temperature along the length of the kiln. While the deviation in some cases between literature and calculated values is relatively small, there are cases where it is quite significant ranging from 1.56% up to 52.49%, thus making the adoption of temperature-dependence of C_p necessary. Establishing a more accurate relation for the specific heat capacity leads to a better energy balance inside the kiln which along with other improvements can lead to a decrease in the energy consumed.

KEYWORDS: C_p calculation, cement production, energy consumption

INTRODUCTION

Depending on the type of the kiln (wet, dry, semi-dry) the energy consumption varies due to different percentage of moisture in the raw meal that needs to be evaporated[5]. Typically in the wet process kiln the raw meal contains 36% moisture while in the dry type that percentage is 0.5%[6]. Due to that the energy consumption is 3.4 GJ/ton of clinker produced for the dry type and 5.29 GJ/ton for the wet kiln[3] so the process requires approximately 4 GJ/ton. Concurrently, for each tone of clinker produced an equivalent amount of emissions is released in the atmosphere consisting of carbon dioxide, nitrogen oxide, methane and chlorofluorocarbons (greenhouse effect gases)[7–9]. A well-designed rotary kiln is essential as it can reduce the emissions and improve the energy efficiency while preserving the final product quality. The rotary kiln under investigation is of the dry type so its energy consumption is already lower than other types. Nevertheless, kiln parameters, including those included in the energy balance equation, must be optimized in order to reduce emissions or consumption. The fluidized bed's specific heat capacity was the one parameter that stood out among the rest. It was observed that the specific heat capacity of bed remained constant throughout the process although temperatures inside the rotary kiln, for the reactions to take place, range from approximately 800 K in the kiln inlet to almost 1600 K near the flame of the burner. Thus, the aim of this research was to find an expression for the heat capacity of the fluidized bed so that the energy balance equation would be more efficient for the whole process.

METHODOLOGY

The raw material of the clinker production consists of a mixture of clay and finely grounded limestone that is processed inside the rotary kiln. The main compounds of clinker minerals are C_2S [$(2CaO{\cdot}SiO_2)$], C_3S [$(3CaO{\cdot}SiO_2)$], C_3A [$(3CaO{\cdot}Al_2O_3)$], C_4AF [$(4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3)$] that are also the main products of the reactions taking place into the kiln. For simplification the sintering reactions are limited to five with their temperatures ranges being quite high.

Table 1. *Main reactions of clinkerization inside the rotary kiln.*

	Reactions	Temperature range [K]
1	$CaCO_3 \rightarrow CaO + CO_2$	823-1233
2	$2CaO + SiO_2 \rightarrow C_2S$	873-1573
3	$C_2S + CaO \rightarrow C_3S$	1473-1553
4	$3CaO + Al_2O_3 \rightarrow C_3A$	1453-1553
5	$4CaO + Al_2O_3 + Fe_2O_3 \rightarrow C_4AF$	1453-1553
6	$Clinker_{sol} \rightarrow Clinker_{liq}$	>1553

For the C_p calculation, based on the reactions of Table 1, the C_p equations as a function of temperature were retrieved from Perry's handbook[10] for the components $CaCO_3$, CaO, SiO_2, Al_2O_3, Fe_2O_3 of the system.

- $CaCO_3$

$$C_p = 19.68 + 0.01189T - \frac{307600}{T^2} \qquad 273 < T < 1033 \tag{1}$$

- CaO

$$C_p = 10 + 0.00484T - \frac{108000}{T^2} \qquad 273 < T < 1173 \tag{2}$$

- SiO_2, quartz a

$$C_p = 10.87 + 0.008712T - \frac{241200}{T^2} \qquad 273 < T < 848 \tag{3}$$

- SiO_2, quartz β

$$C_p = 10.95 + 0.00550T \qquad 848 < T < 1873 \tag{4}$$

- Al_2O_3

$$C_p = 22.08 + 0.008971T - \frac{522500}{T^2} \qquad 273 < T < 1973 \tag{5}$$

- Fe_2O_3

$$C_p = 24.72 + 0.01604T - \frac{423400}{T^2} \qquad 273 < T < 1097 \tag{6}$$

Thereafter, for the dicalcium silicate C_2S, tricalcium silicate C_3S, tricalcium aluminate C_3A and tetracalicium aluminoferrite C_4AF considering the work of Mai et al.[11], in which the known property was the specific heat in constant volume *(C_v)* within a temperature range of 0 K to 800K, is was assumed that the value of C_p is almost equal to C_v. For ideal gases the relation between C_p and C_v is given as $C_p - C_v = R$ but, when it comes to solids or liquids the value of $C_p - C_v$ is so small that is considered negligible for most cases[12], as solids are considered incompressible[12]. Considering that energy and volume are extensive thermodynamic quantities, in a mixture both C_p and C_v can be expressed as a sum of the individual components. According to the reproduced diagrams of C_v from literature, as a function of temperature, it can be assumed that after 800 K the C_v value of each compound remains constant, this hypothesis is needed because inside the cement kiln the temperature ranges between 800 – 1600 K approximately[4].

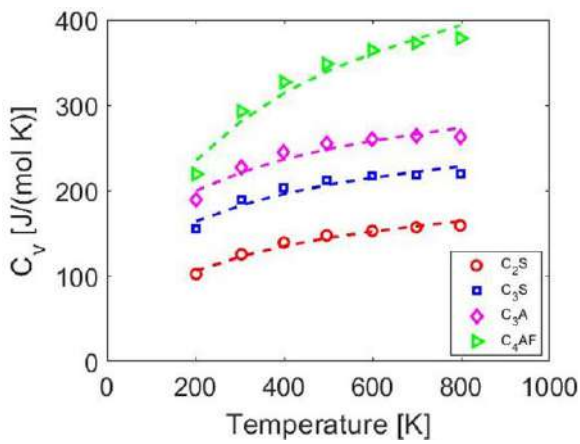

***Figure 1**. Symbols representing literature data for specific heat capacity in constant volume from [11] and dotted lines of the same color are the curve fitting.*

So, the specific heat capacity at constant pressure can be written as a linear combination of the individual phases [13]. Combining the heat capacities of pure components from both the equations and the diagrams with the compositions of the components along the kiln that were taken from the literature it becomes possible to calculate the needed parameter. The mixing rule for the calculation is based on the work of Abdolhosseini Qomi et al.[13] and therefore the relation is described as follows:

$$Cp_{mix}= (1-n)\sum_{i=1}^{m} \Phi_{Ri} Cp_{Ri} + n \sum_{i=1}^{m} \Phi_{Pi} Cp_{Pi} \tag{7}$$

RESULTS AND DISCUSSION

It can be concluded that the heat capacity of the fluidized bed varies along the kiln length depending on the composition and temperature changes. The calculated value is not constant and that is because, the extracted information for the concentration profiles have differences, as some of the parameter values used were not in fully agreement. Since there is a strong dependence on the temperature and the composition of the calculated C_p, according to the mixing rule used, it is concluded that the value of C_p should not be constant along the kiln length and it is encouraged to use the variable one in the calculations. Using a more realistic value of C_p in the simulations of the fluidized bed of the kiln affects the system and more precisely the composition profiles of clinker along the kiln length.

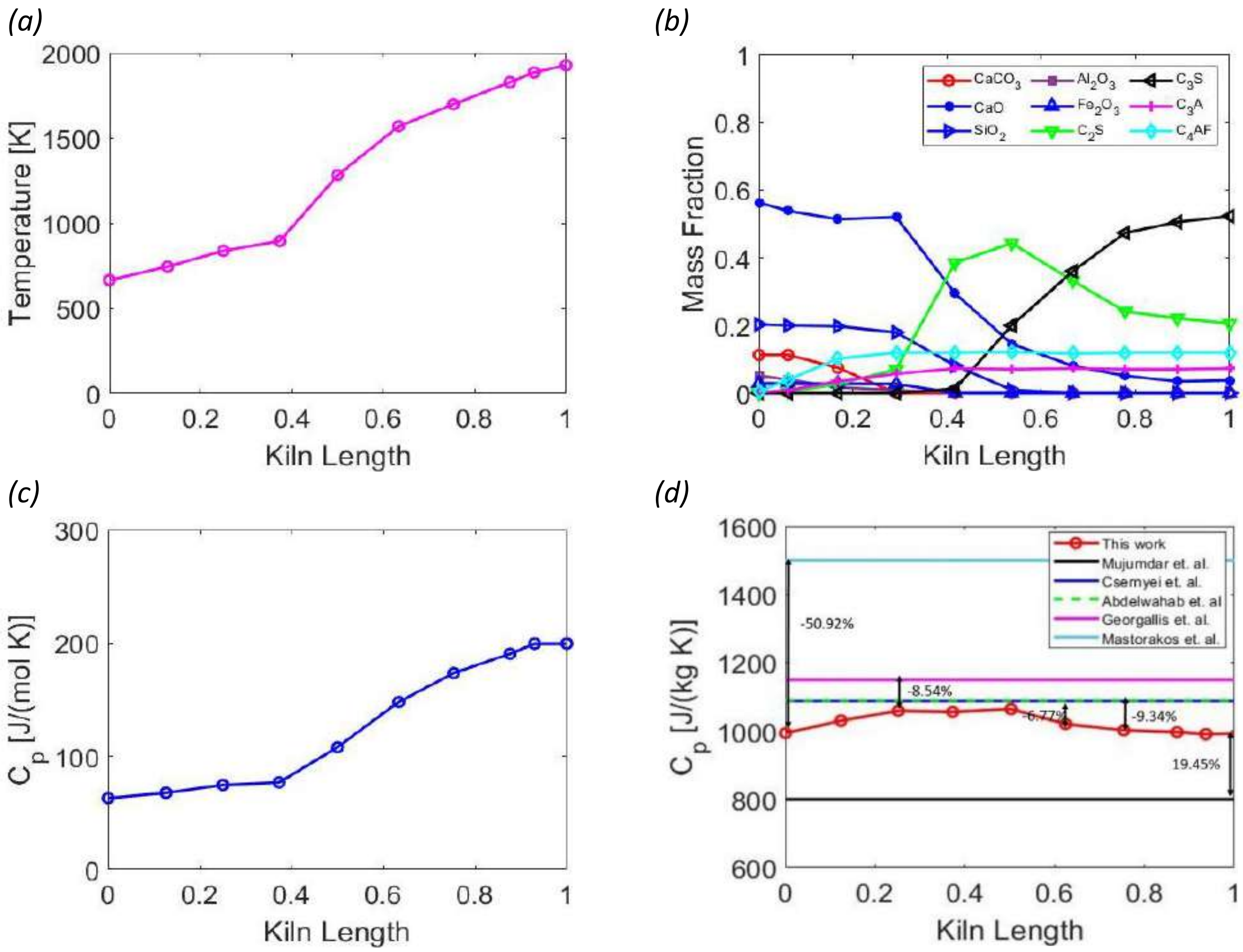

Figure 2. *Different parameters plotted as a function of the dimensionless rotary kiln length. Literature data[1] for: (a) solid bed temperature, and (b) solid bed composition expressed as mass fraction. (c) Calculated C_p of the solid mixture of the kiln bed in [J/ (mol K)]. (d) Comparison of the calculated (denoted with red circles) C_p (in [J/ (kg K)]) and the values used by Mungyeko Bisulandu and Marias, 2021 (denoted with the solids lines). Solid lines connecting the symbols are guides to the eye only.*
References for constant C_p used: Mujumdar et al.[14], Csernyei et al.[15], Abdelwahab et.al.[16], Georgallis et. al.[17], Mastorakos et. al.[4].

Establishing a more precise relation for the specific heat capacity leads to a better energy balance inside the kiln which along with other improvements can lead to a decrease in the energy consumed. Hence, for more accurate calculations of the compositions and the temperature profile inside the rotary kiln it is recommended to use a variable C_p as the difference between the two values (calculated and from literature) fluctuates, depending on the case, between 6.77% up to 50.92%.

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