Life Cycle Cost Analysis of Karl Fischer water determinaton for moisture sensitive materials for electric vehicles and pharmaceutical use

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Abstract—**When using materials that are sensitive to moisture and water, unwanted side reactions can result in the formation of by-products, toxic substances, reduced yields and even occupational accidents. In the pharmaceutical industry and in the production of Li-ion batteries, humidity, moisture and water control of raw materials and intermediate products are of particular importance. One suitable method is Karl Fischer titration. In this work, a life cycle cost analysis of Karl Fischer water determination is presented.**

Keywords— life cycles assessment, life cycle cost, LCA, LCC, Li-ion batteries, APIs, Karl Fischer titration, water, moisture

I. INTRODUCTION

Water is also a solvent, a reactant and a reagent, covering 71% of the Earth's surface, in solid form as ice, in liquid form as water, in gaseous form as vapour. There are many materials, production processes and methods that are sensitive to the presence or absence of water in a particular state, or that can be combined with certain substances or effects to produce undesirable processes, such as mould in residential buildings, unworkable pasta with insufficient moisture, drought and drying, sawdust splashing, accelerated degradation due to microflora or instability, for example in the case of pharmaceuticals.

In many areas of industry and research and development, the provision of adequate water content is of utmost importance [1, 2]. In this article, we focus on water and moisture sensitive materials, and analyse the water content and moisture determination methods for their processing from a life cycle cost perspective.

Life cycle analysis is an environmental management toolkit for evaluating the environmental impact of process steps from the raw material life cycle and production life cycle to waste and recycling (Fig. 1.). It is based on the ISO 14040 and ISO 14044 standards [3, 4]. The evaluation can be performed manually or by software, and there are several evaluation methods to choose from, CML and ReCiPe methods [5, 6, 7] being particularly suitable for the evaluation of chemical-intensive processes and procedures.

Life-cycle cost analysis can be used to estimate the net present value of the costs incurred in a given life-cycle phase, using USD/1000 measurements/year as the unit of measurement. Life cycle cost analysis, together with life cycle analysis, is part of sustainable development and helps to develop a circular economy approach.

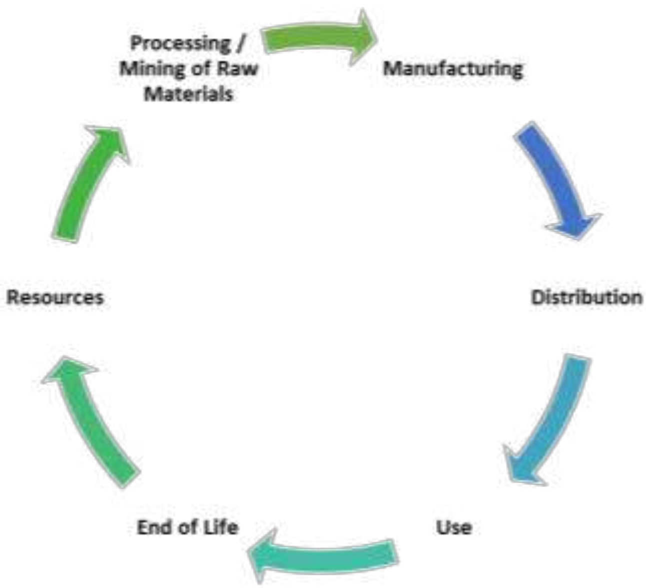

Fig. 1. Life Cycle

Determination of water and moisture content

There are several methods available, depending on the expected water content, the accuracy of the measurement, whether the material is heat sensitive, the type of instrumentation available or applicable to the production site and environment, the frequency of measurement, whether it can be automated if necessary, and whether any permits or special qualifications are required.

For high water contents, e.g. soil samples, non-heat-sensitive precipitates, a rapid moisture determination may be used, for hygroscopic materials vacuum drying, or a lyophilisation procedure for heat-sensitive materials, biological samples, and then calculation of water content based on mass measurement. X-ray and IR instruments are used to determine the water content of insensitive anhydrous materials.

Chemical measurements include gas evolution reactions and Karl Fisher titration, the latter being used to measure water contents from 1 ppm to 100 % efficiently.

Karl Fischer water determination

The principle of water determination is based on the oxidation of elemental iodine. The measuring solution typically consists of sulphur dioxide, iodine and organic base absorbed in methanol, and the end-point detection can be by fading of the solution colour or by an indicator electrode.

Particularly low water content or extremely moisture sensitive substances are usually tested by coulometric titration, where the solution contains potassium iodide rather than elemental iodine, which is released at the anode and reacts with the water content of the sample to produce the amount of charge required to generate elemental iodine, which gives the amount of water in the sample.

In coulometric measurements, the water content of the sample is between 1 ppm and 5 %, while in volumetric measurements the water content is above 100 ppm.

A simplified reaction equation of the reaction that takes place, where RN is the nitrogen-containing organic base, e.g. pyridine or imidazole, where alkylsulphate salt and hydrogen iodide compound formed.

$$H_2O + I_2 + SO_2 + CH_3OH + 3RN \rightarrow (RNH)SO_4CH_3 + 2\,(RNH)I$$

The general composition of the reagents is described in the table below (Table I.). It can be clearly seen that in coulometric reagents for the measurement of substances with low water content (less than 5 %), in addition to methanol, the halogenated organic compound chloroform is also present as a solvent in significant quantities, but this reagent usually does not contain diethanolamine.

TABLE I. COMPOSITION OF KARL FISCHER REAGENTS

Method	**Volumetric Titration Reagent**		**Coulometric Titration Reagent**	
Function	Component	composition, weight %	Component	composition, weight %
Solvent	Methanol	40	Methanol	40
			Chloroform	31
Organic Base (pH Buffer)	Imidazole	12	Imidazole	12
	Diethanol-amine	8		
Reagent	Sulfur dioxide	10	Sulfur dioxide	7
Iodine Reagent	Iodine, elemental	10	Potassium iodide	10

Use in the pharmaceutical industry

Moisture-sensitive substances such as metal hydrides lithium aluminium hydride, amides such as sodium amide, Grignard reagents used in the production of active substances such as the analgesic tramadol, the anti-inflammatory, antipyretic and analgesic naproxen and ibuprofen [8]. Numerous examples include the active substance remdesivir [9] used in the Covid-pandemic [10]. The water sensitivity of Grignard reagents is known, in the C-glycosolation reaction [11], or the reaction of degradable boron trichloride at -40 °C or triethylamine at -78 °C with the reaction mixture, simply because of the sub-zero temperatures, no water can be present in the system to avoid damaging the reactors.

For stability and shelf-life, a specific moisture content is required for many pharmaceutical substances such as theophylline [11] used for asthma or levothyroxine [12] used in hypothyroidism.

Inappropriate conditions, excessive moisture or water content can destroy an entire batch, cause unwanted side reactions, lead to the formation of toxic substances or result in a mixture that is difficult to purify and may have low yields.

The importance of moisture content for lithium-ion batteries

During the production of lithium-ion battery cells, there are several critical points where the moisture content is as tightly controlled as possible and kept sufficiently low to prevent side reactions such as the formation of highly toxic and corrosive hydrogen fluoride [13] gas (a major concern from a health and safety point of view), and the reduction of the active ingredient content of NCM due to the action of water and air: lithium hydroxide formation and subsequent carbonation [14, 15], in-use failure and loss of cell capacity and life expectancy [16].

Strict quality control throughout the entire manufacturing process is important [14].

Manufacturing processes involve several drying steps, where the humidity of the manufacturing environment is set to freezing between -30 and -40 °C, while the water content of materials, such as the separator film, which has a ceramic coating that can absorb more moisture due to its porous surface, must be constantly monitored. For lithium-ion battery production, the Karl Fischer water determination [17] is ideal, very low water content is required, therefore a coulometric method is recommended.

Life Cycle Costs

The life-cycle cost of water determination in US dollars (USD) per 1000 measurements per year is illustrated in Fig. 2. For the calculation, the initial cost and installation cost as well as the termination cost were calculated for 10 years, while the other factors were calculated for 1 year. In the case of coulometric titration, it can be seen that the cost factors are higher, due to the cost of the reagent and its hazardousness, since it contains halogenated organic material, and the cost of waste disposal.

We used the prices and change rates valid in Hungary on 20th of August.

The calcualtions are based on 10 years of equipment runtime.

The initial cost includes the measuring system and all the basic equipment needed, such as reagents, standards. Installation costs are related to the infrastructure required for the operation of the measuring system, the measuring site and its surrounding environment, commissioning and service costs. Energy costs are the cost of the electricity used in the operation.

Operating costs include the cost of reagents, electrodes, waste containers, filters, which are constantly consumed. Service and maintenance costs are the periodic and routine (due to breakdown) material and service charges. Environmental costs are the costs of waste treatment.

Is it the cost of quality?

At the current market price, 1 tonne of NCM costs 40.000 USD, the total cost of coulometric measurements per 1000 measurements is only 15.690 USD, which means that only considering the cost of this raw material, excluding the initial costs of performing the measurements, we can prevent the production of defective semi-finished and finished products from the resulting NCM, not counting the costs of handling and transporting the resulting production waste.

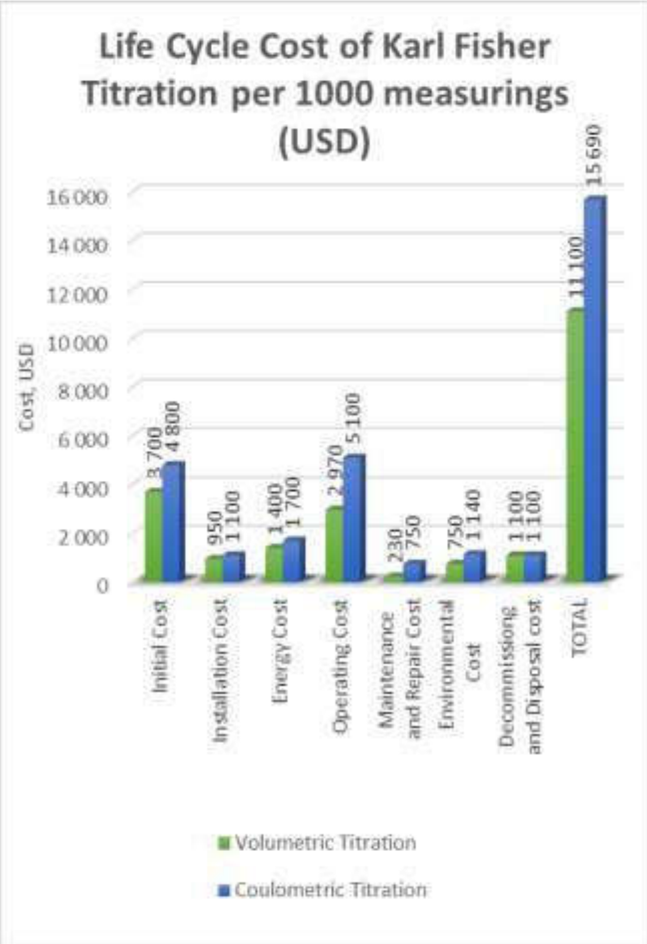

Fig. 2. Life Cycle Costs

To give an example from the pharmaceutical industry, if ibuprofen is priced at USD 25/kg, again excluding the additional cost of side effects and waste, the selling price of 630 kg of high quality ibuprofen is equivalent to the annual cost (Fig. 3.).

Karl Fisher measurement is essential to keep production costs low. Waste treatment costs due to side reactions, waste transport, waste disposal are a significant burden for companies. By strictly controlling the processes, strictly respecting the limits, professionally carrying out the measurements and their evaluation with due care, the costs can be controlled and the quality of the semi-finished and finished products can be guaranteed to the users.

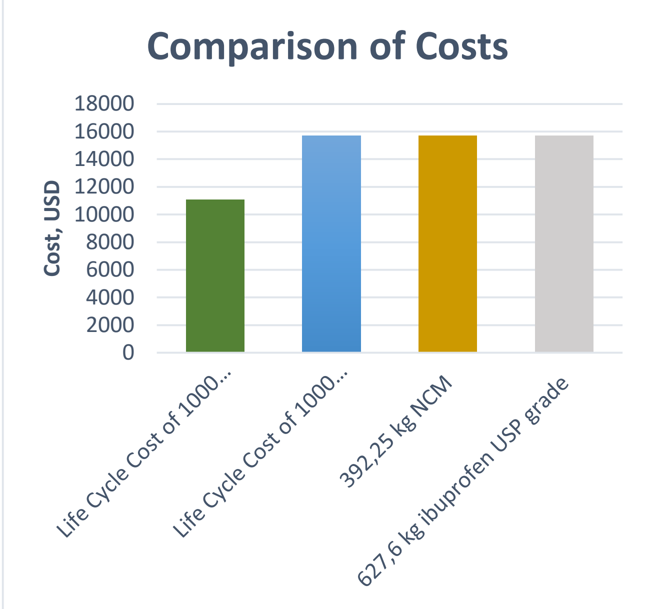

Fig. 3. Comparison of Costs

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II. Conclusions

The determination of water content is very important to reduce scrap costs, prevent accidents and side reactions and ensure the desired quality. Stability and durability are also very important. In the pharmaceutical industry and for Li-ion battery cells, the specifications for moisture and water content and humidity must be strictly observed. In Hungary, using prices and exchange rates valid on 20 August 2023, the life cycle cost of 1000 measurements is comparable to about 400 kg of NCM or 600 kg of ibuprofen using the coulometric measurement system, excluding the waste disposal costs due to side reactions. Apart from the initial cost, even for very small batches it is worth maintaining the measuring system.

III. SUMMARY

Data without sufficient resolution will give an incorrect life-cycle result. Appropriate geography is also important, and the energy mix can vary significantly. Some materials are not currently available in any life cycle inventory database, and can be further developed either from their own data or by estimation. Once the purpose of the study has been defined, it can be decided which impact assessment method will be optimal.

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