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Grease Production, CO₂ emission.... a New Relationship!

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Abstract

Manufacturing conventional lithium grease is a very energy intensive operation and, surprisingly, to the knowledge of the authors, no one prior to a recent technical paper [1] has studied the energy consumption and possible environment impact of the grease manufacturing process associated with the base oil used. It is well known that carbon dioxide has been shown to be the major contributor to greenhouse emissions and global warming and energy consumption can be directly related to the manmade contribution of this gas.

The aim of this paper is to measure the energy consumption on an industrial scale production of conventional lithium grease when a pressurised reactor is used and is further compared to traditional open kettle reactor. All the process parameters have been kept constant as well as the viscosity of the base oils used. The selected based oils are naphthenic and paraffinic Group I that are typically used in the preparation of lubricating greases.

The total energy (electrical for mechanical operations such as pumping, mixing and homogenizing, as well as fuel for heating) consumed for production purposes is recorded for all production stages: vessel charging, cooking, cooling/diluting and homogenizing. The measured energy consumption used for each batch is then converted to normalized CO_2 emission and savings in utilities for each of the batches evaluated. In order to make this comparative study more accurate, the finished greases have also been characterized according to the specification required by the end-users.

In total, eight full-scale lithium-based greases were manufactured using two different base oil viscosities. Considering the batches with the same base oil viscosity, it can be concluded that, for the grease with an ISO VG 220 oil, an overall reduction in CO_2 emissions of 21.5% per metric ton of produced product can be achieved by switching from a paraffinic base oil in an open kettle to a paraffinic/naphthenic base oil mixture in the Contactor™ reactor.

The authors believe that the outcome of this study could be a milestone in assessing grease production in terms of significant reduction of CO_2 emissions and increase awareness of the impact of our industry in the global environment.

1. Introduction

The basic technology for production of soap type greases has been essentially unchanged for the last fifty or more years. This is certainly true for the type of lubricating grease that is most commonly used in the global market, namely lithium-based greases, which typically represent 75 percent of global grease production [2]. In a way, the production methods utilized by our industry have remained stagnant, while the products that are the outcome of this process are becoming ever more sophisticated and suitable for high end and extreme applications, often thanks to the use of more efficient additives.

Recently, the grease manufacturers are witnessing a number of challenges, such as a rapid increase in the price of lithium hydroxide due to the extreme growth of the lithium-based battery industry. Some of the recent publications (e.g. Fathi-Najafi et.al. [3]) are suggesting that, by using high viscous naphthenic oils, the thickener content could be reduced to about 4.6 (wt.%) in the case of conventional lithium grease when targeting NLGI grade 2 consistency.

Another challenge that grease makers sooner or later should cope with is how manufacturing of lubricating greases can be optimized from an energy consumption point of view. The reduction of the energy required for grease production using base oils of different solvencies has been demonstrated in the past [1] on a laboratory scale, in which It was demonstrated that, by using naphthenic versus paraffinic base oils, a reduction of approximately 12 percent in energy consumption could be obtained. The findings from that pilot plant project was then transferred to this full-scale production study. Hence, the aim of this paper is to demonstrate how the total energy consumption and, subsequently, CO_2 emission per mass of fully formulated conventional grease could be obtained.

2. Background to the manufacturing process of lithium-based greases

Conventional lithium grease is manufactured in a two-stage process. The first consists of the reaction stage (cooking) and the latter one being the finishing stage. Typically, two separate vessels are used for the two steps, with the cooking stage being carried out in either an open kettle under atmospheric pressure or a closed kettle, as shown in Figure 1. In the closed process, either an autoclave or a Contactor^{TM} reactor (as shown in Figure 2), where the reaction occurs under pressure, is typically used. In the Contactor, the design also involves increased heat and mass transfer rates, thus enhancing dispersion and further reducing production times. This has been demonstrated in numerous studies [4], with the process time being significantly lower when the STRATCO® Contactor^{TM} technology is utilized.

Typically, for the finishing stage, scraped-wall vessels with cooling (and sometimes heating) capabilities are used in conjunction with various mixing geometries that will depend on a number of factors, such as the vessel overall size, width to height ratio and type of product it has been designed to handle. The finishing vessel is connected to the auxiliary equipment required to produce a commercial grease, such as mills, homogenizers, filters, deaerators, etc. In some cases, "hot milling" is done during the cooking stage.
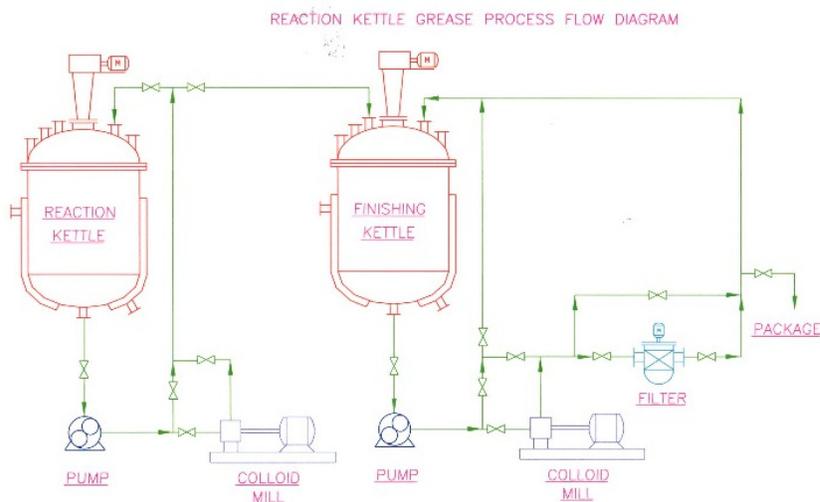
REACTION KETTLE GREASE PROCESS FLOW DIAGRAM

Figure 1. Typical grease production process, Kettle process.

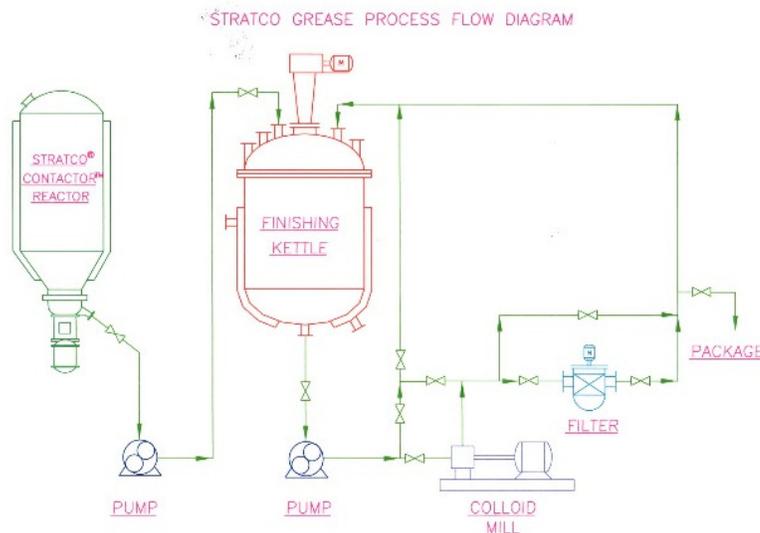STRATCO GREASE PROCESS FLOW DIAGRAM

Figure 2. Typical grease production process, STRATCO® Contactor™ process.

Despite advances in the equipment used to finish the product, such as high-pressure homogenizers, self-cleaning filters and in line measuring/monitoring, very little has changed in the way the fatty acid and alkali are reacted or in the way that the grease is handled inside the finishing kettle in the past 60 years. Some attempts have been made to produce grease in a continuous process, but application in the field is very limited with only a few facilities worldwide having the required facilities and capacities to produce using such a mode of operation.

3. Energy requirements for lubricating grease manufacturing

With the development of electrically powered commercial and passenger vehicles, the role of lubricating grease will become increasingly important with numerous studies being carried out to show the energy efficiency of modern soap type lubricating greases for electrical motor applications. According to studies [5] the energy dissipated in large electric motors can be reduced by 60% at lower speeds (1000 rpm) and up to 90% at higher speeds (2500 rpm) when the correct grease is being used. Comparing this to modern energy conserving engine oils, such as API SN RC, we can see that the aim is a reduction of 0.9 percent in energy consumption of the internal combustion engine [6].

As one might imagine, the energy saving potential in the forthcoming years can be significant with the use of the more optimized grease. But, then how much energy can be conserved in the production stage of lubricating grease? It is well known that, in comparison to other lubrication products used for commercial and industrial applications, lubricating greases are significantly more energy intensive in the production stage.

For the production of lubricating oil products, typically 2.5 - 4 kWh per metric ton of product are required to mix and pump the product, as well as low intensity heating to, usually, below 70 (^{o}C), which is a much simpler process of blending, as shown in Figure 3. Comparing this to lithium grease where, in the reaction stage, the temperature needs to approach 200 (^{o}C) and the mixing and pumping energy is significantly higher due to the highly viscous nature of the product, it is understandable that the overall energy requirements are also more significant. As a matter of fact, through theoretical calculations, the energy requirements for heating during grease production – including the heat of reaction – are approximately seven times the energy required to heat the same base oil in formulating a lubricating oil. Similarly, based purely on the product viscometrics and not the non-Newtonian nature of grease, the energy requirement to mix and pump a grease versus a typical lubricating oil will be significantly higher.
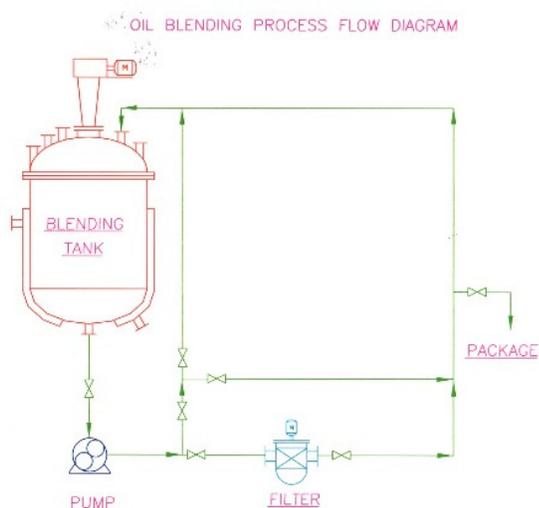

Figure 3. Typical oil blending production process.

In principal, for any lubricants manufacturer, making process improvements, such as improving an oil/gas heater efficiency, higher heating medium circulation speed, improved insulation, more efficient electric motors on pumps, etc. would, generally, provide a seven-fold energy benefit on grease production as

compared to oil blending. This is based on the theoretical energy requirements of each process, without taking into the account any system losses, overdesign or other factors that will limit efficiency. Considering this, the biggest portion of potential savings can be seen on the heating energy that accounts for almost 80 percent in a typical grease production process. The above implies that, when looking at optimizing the energy usage of a lubricants manufacturing facility, starting with the grease production will have greater impact both on economic and environmental terms.

The largest proportion of energy used today is linked to fossil fuel. The heating oil or gas consumed for the production process can be directly correlated to CO_2 emissions. The electricity consumed for mixing, pumping and auxiliary uses is indirectly related to fossil fuel as the source of power generation is most often linked to fuels ranging from coal to oil, natural gas and renewable sources. The fuel mix is often variable and will need to be verified by the utility supplier. As a result of any process optimization, the reduction of energy will also lead to a reduction in CO_2 emissions and, thus, the carbon footprint linked with the product being put on the market, even before this is put to use. The reduction of the energy requirements for grease production using base oils of different solvencies has been demonstrated in the past [1], in which It was shown by using naphthenic versus paraffinic base oils a reduction of approximately 12 percent in energy consumption could be obtained, as shown in Table 1. The comparative results from that pilot plant project formed the basis of this full-scale production study. If the correlation is demonstrated on an industrial scale, then a reduction of the total energy consumption, and subsequently CO_2 emission per mass of fully formulated conventional grease, could be obtained.

Properties	Method	Grease A	Grease B	Grease C
Base oil	-	T110	SN525	T110:SN525 (1:1)
Base oil Type	-	Naphthenic	Paraffinic	Naph+Paraf
Thickener content, wt.%	-	7.92	9.02	7.82
Pen (60), mm^{-1}	ASTM D217	239	258	272
Dropping Point, °C	ASTM D2265	206	207	209
Energy Consumption, kWh	-	15	17	15

Table 1. Energy consumption and thickener content for conventional lithium-based greases, [1].

4. Grease Production

A series of batches were produced on an industrial-scale under closely monitored conditions. A total of eight batches were evaluated. The selected viscosity grades (VG ISO 100 and VG ISO 220) were chosen since these are the typical grades for multipurpose lithium greases in the industry. The production stage, time, temperature, electricity and LPG consumption were recorded throughout each batch. Temperature inside the vessel was recorded continually during the cooking stage and measured by contact and infrared thermometers during the finishing stages.

Remarks	Type of Cooking Vessel	Type of Base Oil	Viscosity of the Oil @40°C, [mm²/s]
TB 01	Pressurised (Stratco)	Naphthenic	100
TB 02	Pressurised (Stratco)	Naphthenic	220
TB 03	Pressurised (Stratco)	Paraffinic	220
TB 04	Pressurised (Stratco)	Naphthenic + Paraffinic	220
TB 05	Atmospheric (Open)	Paraffinic	100
TB 06	Pressurised (Stratco)	Paraffinic	100
TB 07	Atmospheric (Open)	Naphthenic + Paraffinic	220
TB 08	Pressurised (Stratco)	Naphthenic + Paraffinic	100

Table 2. Batch base oil profile data.

The base oil profiles of the eight batches are presented in Table 4 and selected characteristics of the base oils used in this study are shown in Table 3.

Remarks	Visc. @40 °C, [mm²/s]	Visc. @100 °C, [mm²/s]	Viscosity Index	Aniline Point, [°C]	Pour Point, [°C]	S-content, [wt.%]
Paraffinic 1	103	11.1	92	108	- 9	0.44
Paraffinic 2	218	18.7	95	105	- 8	0.52
Naphthenic 1	22.3	3.7	-3	75	- 45	0.06
Naphthenic 2	150	10.2	8	89	- 27	0.13
Naphthenic 3	600	21.5	-12	89	- 12	0.30

Table 3. Typical characteristics of the base oils.

In order for an unbiased comparison of produced batches to be made, a target of grease consistency with worked penetration of 270 (mm⁻¹) was set. Also, based on prior knowledge of the art, the thickener base was adjusted accordingly between batches in order to produce similar quantities of finished grease. This approach was chosen as similar batch sizes in the finishing stage mean that variations in energy required for the finishing stage (mixing, cooling, homogenizing, etc.) will only be affected by the thickener content and the viscosity of the base oil.

The final grease was enriched with a commercial antioxidant and anti-wear additive package at a typical treat rate recommended by the supplier. The nature of these additives does not affect the rheology of the product and were required to convert the base grease into a formulated commercial product, as was required in the scope of this study.

During the production phase of the test batches, several biases were observed, namely, the ambient temperature and the time between production batches. Ambient temperature affects the energy requirement of the production process in the following two ways: a) energy required to pump the oil from the storage tank to the cooking and finishing vessels and b) the energy required to heat the base oil from ambient to the reaction temperature. During the test period the ambient temperature varied with a $\Delta T=17$ (°C), which affected the viscosity up to + 220 percent, depending on the base oil type. Also, with an average specific heat capacity of 1.67 (kJ/kg K) [8], approximately 15 (kWh) of heating energy variation can be attributed to ambient temperature differences.

Time between production batches will affect the residual heat in the production system, particularly in the Contactor, where an energy consumption variation of up to 12.2 percent was observed between starting a batch in a cold vessel after prolonged dormancy and back-to-back batch production. In order to compensate for the variability described above, a starting point of 70 (^{o}C) was selected for the energy measurements.

5. Performance characteristics of the produced greases

Throughout this study, it was critical to demonstrate that the produced greases not only met the production parameters specified in the above paragraph but also met the required performance characteristic of a commercial grease, as required when full-scale production is done.

The test parameters evaluated provide the required evidence that each of the full-scale batches produced are representative of a fully formulated commercial grease. As previously mentioned, a number of parameters, such as oxidation stability, were enhanced using commercial additives. The intent is to further demonstrate that these properties can also be affected and, as a matter of fact, be enhanced by manipulating the appropriate manufacturing parameters and/or starting components of the grease. Notably, that all the process parameters were kept the same when these batches were produced.

One parameter that was kept outside typical commercial specification is the worked penetration of the test batches. Typically, greases will be marketed with a worked penetration 280 - 285 (mm^{-1}). However, the test batches were further treated with performance enhancing additives that brought the penetration to the required value. Table 4 and 5 show some of the measured characteristics of the greases.

Characteristics	Test Method	TB 01	TB 05	TB 06	TB 08
Thickener content (wet), [wt.%]	-	7.2	8.9	8.2	7.1
Type of Base Oil	-	Naph.	Paraf.	Paraf.	Naph. +Paraf.
Type of Cooking Vessel	-	Stratco Contactor	Open Kettle	Stratco Contactor	Stratco Contactor
Pen after 60 strokes, [mm^{-1}]	D 217	264	274	270	266
Dropping point, [^{o}C]	IP 396-02	200	203	201	202
Oil separation, [wt. %]	D 1742	< 0.5	3.61	2.84	2.12
Water washout, [wt. %]	D 1264-18	6.3	4.3	2.7	5.9
Diff in Pen. after 10^5 strokes, [mm^{-1}]	D 217	+ 31	+ 27	+ 35	+ 46
4-Ball wear, [mm]	D2266	0.95	0.82	0.64	0.88
Copper corrosion, [rating]	D4048	1b	1a	1a	1a
Oxidation stability@ 140 ^{o}C, [min]	D7575	510	769	1042	762

Table 4. Characteristics of the greases (VG ISO 100).

As stated in Table 4, lower thickener content can be obtained by using naphthenic (TB 01) in lieu of paraffinic (TB 05). In fact, TB 08, which is a blend of naphthenic and paraffinic oil, confirms that the lower

soap content can be obtained, even if partly naphthenic oil is used. This batch (TB 08) was cooked in naphthenic oil and then cooled by paraffinic oil.

Some of the performance characteristics of these four batches are not in line with each other. For example, the oil separation increases when paraffinic oil is used, but then, on the other hand, the oxidation stability is improved. Water washout follows the soap content.

If we study the impact of manufacturing grease in an open kettle compared with a pressurizsed reactor for the two paraffinic based batches (TB 05 with TB 06), it seems that the use of the pressurised Contactor reactor contributes to: a) a reduction of the soap content and b) a reduction of the risk for the grease being oxidized during the cooking stage. This can be attributed to the fact that, since the reaction time is reduced, the base oil is subjected to higher temperatures for a shorter period. Furthermore, the pressurization of the process using the steam generated by the chemical reaction limits the ingress of atmospheric oxygen to the system, also contributing to the improved results.

Surprisingly, when the average viscosity of the base oil was increased from 100 (mm^2/s) to 220 (mm^2/s), a number of the characteristics were improved. Table 5 illustrates some of the measured properties of these greases.

Characteristics	Test Method	TB 02	TB 03	TB 04	TB 07
Thickener content (wet), [wt.%]	-	4.8	7.5	5.4	7.6
Type of Base Oil	-	Naphthenic	Paraffinic	Naphthenic +Paraffinic	Naphthenic +Paraffinic
Type of Cooking Vessel	-	Stratco Contactor	Stratco Contactor	Stratco Contactor	Open Kettle
Pen. after 60 strokes, [mm^{-1}]	ASTMD 217	269	273	278	273
Dropping Point, [^{o}C]	IP 396-02	205	207	208	204
Oil Separation, [wt. %]	ASTM D 1742	< 0.5	1.96	2.85	3.74
Water Washout, [wt. %]	ASTM D 1264-18	4.7	4.7	3.6	4.5
Diff in Pen. after 10^5 str., [mm^{-1}]	ASTMD 217	+ 46	+ 33	+ 44	+ 31
4-Ball Wear, [mm]	ASTM D 2266	0.68	0.61	0.65	0.61
Copper Corrosion, [rating]	ASTM D 4048	1a	1a	1a	1a
Oxidation Stability@ 140 ^{o}C, [min]	ASTM D 7575	750	1082	1099	861
Flow Pressure @ -25 ^{o}C, [hPa]	DIN 51805	620	1320	695	N/A
Flow Pressure @ -30 ^{o}C, [hPa]	DIN 51805	1020	1595	1145	N/A

Table 5. Characteristics of the greases (VG ISO 220).

If we compare the greases that are cooked in the pressurised reactor (TB 02, TB 03 and TB 04), the significantly lower thickener content in the case of TB 02 and TB 04 can only be related to the use of the naphthenic oils with higher degree of solvency and viscosity.

The measured characteristics of the greases also indicate the following:

a) the oil separation increases with the use of paraffinic oil, regardless the type of cooking vessel.

b) the oxidation stability for greases that are cooked in the pressurised reactor and contain paraffinic oil (TB 03 and TB 04) is better than the other batches. However, a result of 750 (min) or higher can still be regarded as good to excellent.

c) the flow pressure, which is a good indication of the degree of the pumpability of a grease is, as expected, in favor of the greases that contain naphthenic oils.

d) all other characteristics are in line with each other and within the frame of the specification for this type of grease.

6. Test batch energy requirements

Two separate parameters have been investigated with regards to the energy requirements of the grease production process. Firstly, the effect of the process equipment used, i.e. atmospheric versus pressurised production vessels. Secondly, the effect of the base oil used. With regards to the latter, the effect of paraffinic versus naphthenic base oil has been investigated. Furthermore, the viscosity of the end product has also been considered by looking at a series of ISO VG 100 and ISO VG 220 base oil blends for the final product.

6.1 The impact of the manufacturing processes on the energy consumption

For each of the stages given below, detailed measurements of time, system temperature and energy requirements (electricity and LPG consumption) were made. As discussed in section 4, in order to minimize any bias attributed to environmental or process conditions, the energy requirements used for test batch comparison are limited to the electricity and LPG values recorded when the base oil for the cooking stage was charged and the temperature in the cooking vessel reached 70 °C. This means that the energy measurements made are biased only by any inefficiencies of the facility installation.

The fuel used for heating purposes was Liquified Petroleum Gas (LPG) which, based on supplier information, is an 80/20 mixture of Butane/Propane providing an equivalent energy output of 31.13 (kWh/m^3). It is noted that LPG measurements were made in m^3 supplied to the burner, but for reporting consistency this has been converted to the equivalent kWh. Based on the information provided by the utility provider, during the period of the production of these batches, approx. 84 percent of the energy was generated from fossil fuel, and 16 percent came from renewable sources.

In order to ensure the validity of the fuel measurements for this study, no other heating operations took place in the production facility during the execution of the test batches. It must be noted that, due to extent of piping, there are expected to be fewer losses in the test batches made in the pressurised vessel compared to the open kettle, based on the distances the heating oil has to travel.

Since we are looking at the energy consumed at the source (actual amount of fuel used), the efficiency of the installation will significantly affect the net result. So, if the theoretical heating energy requirements are used, 134 (kWh/MT) of heating energy are required to heat and react the raw material and heat the base oil and water of the process. Looking at the production schedule summarized in Table 6 for atmospheric versus pressurised production, there is a significant difference in the amount of time required for the cooking stage.

According to the information in Table 6, there is a difference of 225 minutes – almost 4 hours in total production time – when TB 04 and TB 07 are compared. Overall production schedules for all production batches are listed in Appendix A. Looking at the average values, the net gain in terms of time is 232

minutes and the maximum difference is 280 (minutes). This difference is noted between TB 07 and TB 03.

Production Stage / Test Batch	Pressurised, TB 04 (N/P+ISO 220) [min]	Atmospheric, TB 07 (N/P+ISO 220) [min]	Difference (TB 07 – TB 04) [min]
Cooking	245	450	+ 220
Finishing	150	170	+ 20
Homogenizing - Drumming	150	145	- 5
Total Process Time	**540**	**765**	**225**

Table 6. Batch production schedule; *P stands for Paraffinic oil and N for Naphthenic oil.*

The major gain is obtained in the cooking stage of the process, with 220 additional minutes being required when production is carried out in the open kettle. In the finishing stage, there is an additional 15 minutes gained on average, but this is not considered significant, hence it is believed that this step has great potential to be optimized further, based on the manufacturer's experience and the repeatability of produced batches.

These results are not surprising – or new to the industry - as one of the main benefits of using a pressurised vessel is the time required to complete the cooking stage. Focusing on the cooking stage, Figure 4 presents the product temperature as a function of time for all evaluated batches. It can be seen that there is good repeatability of the processes – both Contactor and kettle process. For the pressurised vessel, this can also be seen from the actual temperature recordings shown in Figure 4.
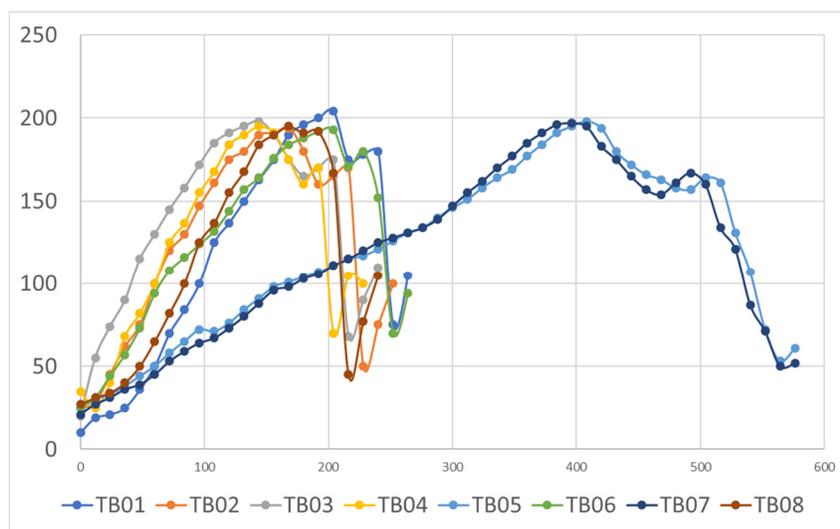

Figure 4. Time vs temperature Charts TB01 to TB08 from reactor charging to reactor discharge.

One of the reasons the temperature ramp is flatter for the atmospheric process is the fact that a larger amount of water is required to assist in the saponification reaction, which absorbs more energy. Looking at the values in Table 7, heating and evaporation of process water accounts for up to 11 percent of the heating energy needs in the atmospheric process. Also, since we have an open system, significantly more energy is lost to the environment compared to using a pressurised kettle. Another reason for the ramp profile is that the heat transfer in the kettle is limited by surface area and lower heat transfer rates due to lower product flow rates within the vessel. These conditions explain the results obtained and listed in Table 7. Comparing the heating energy recorded versus the theoretical energy for lithium grease production in a pressurised vessel (134 kWh per MT) the efficiency of the process, from fuel tank to finished product, varies with an average of 53 percent for the pressurised vessel and 41 percent for the atmospheric process.
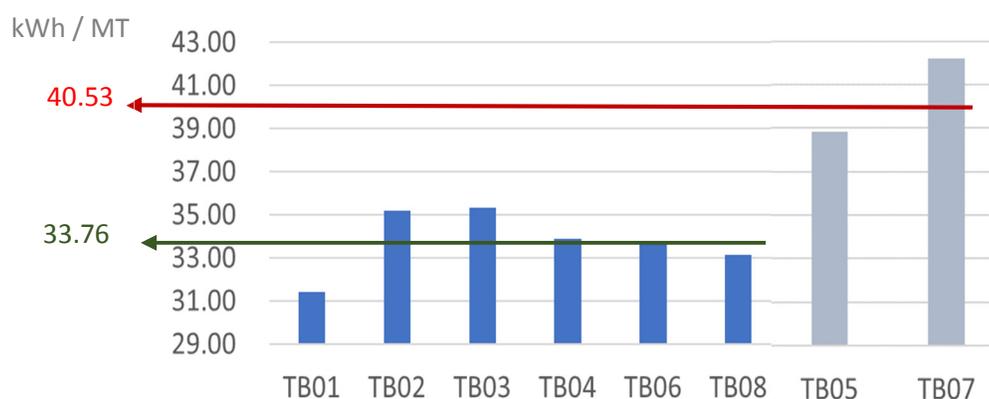

Figure 5. Electricity consumption per MT of grease: atmospheric vs pressurised.

Production Batch	TB 01	TB 02	TB 03	TB 04	TB 06	TB 08	TB 05	TB 07
Cooking	15.79	16.71	17.09	15.57	17.94	16.89	22.13	21.28
Finishing	15.62	18.45	18.23	18.28	19.68	16.25	16.72	20.92
Overall Electricity [kWh/MT]	31.42	35.16	35.32	33.85	37.62	33.14	38.85	42.20
Overall Heating kWh/MT	213.11	187.76	198.66	170.21	191.4	181.76	272.8	234.5
Total Energy, kWh/MT	244.53	222.94	233.99	204.06	229.02	214.9	311.65	276.7

Table 7. Energy requirements for batches in pressurised and atmospheric process.

Looking at the electrical energy for production, it can be seen that there are no significant variations in terms of the amount of electricity per MT of product, particularly in the finishing stages of the grease. This is expected, as energy required is proportional to the amount of product that needs to be processed in this stage. In the cooking stage there are notable variations, as with the heating energy.

In order to accurately evaluate the above stated results, a number of factors need to be considered, namely, the variations in the heating energy between the batches and the variations in the electricity energy in different stages of production, which is summarized in Table 8. All values for energy are normalized per Metric ton (MT) of grease produced. This means that batches that produce a higher yield, or lower thickener content, will benefit from lower results in the cooking stage and, in particular, the heating energy that accounts for approximately 85 percent of all energy required.

Remarks	TB01	TB02	TB03	TB04	TB05	TB06	TB07	TB08
Heating Energy, [%]	87.2	84.2	84.9	83.4	87.5	85.1	84.7	85.3
Electrical Energy, [%]	12.8	15.8	15.1	16.6	12.5	14.9	15.3	14.7

Table 8. Heating vs electrical energy requirement of batches per MT of produced grease.

Considering the average values as shown in Figure 5, it is noted that there is a reduction of approximately 16.7 percent in the electrical energy requirement for pressurised reaction versus atmospheric. Looking at the most (TB 01) and the least (TB 07) electrical energy efficient batches, more than 25 percent difference can be observed. This is something that is overlooked as, typically, the power requirement for the pressurised vessel is much higher than for an open kettle in order to provide the improved mixing rate that is desired.

Remarks	Base Oil	Energy kWh per MT	Normalized Energy	Ranking*
TB 04	N/P (ISO 220)	204.06	1.00	1
TB 02	N (ISO 220)	222.94	1.09	2
TB 08	N/P (ISO 100)	224.9	1.10	3
TB 06	P (ISO 100)	225.02	1.10	4
TB 03	P (ISO 220)	233.99	1.15	5

Table 9. Energy ranking of 5 batches in pressure process. *ranking: 1 lowest to 5 highest.

With regards to the heating energy, it must be noted that all measurements are taken with a hot oil pan as a starting point, but after the first production batch the gas supply was turned off before the cooking stage was completed to take advantage of the residual heat in the furnace and minimize the energy requirements. This explains the reduced LPG consumption in batches following TB 01. This methodology was applied both to all the atmospheric and pressurised batches.

With regards to the electricity consumed, variations between the recorded production stages can be observed and, in particular, in the finishing stage. This can be attributed to the attempts needed to adjust the test batch finished product to the desired consistency. Care was taken so as to make sure the test batch target properties were prioritized, which meant that, for some batches, many minor adjustments had to be made in either the first or the second stage. Nevertheless, for each test batch these two stages included the electrical energy required to mix, pump, homogenize and package the grease.

By comparing the two different processes, the following observations can be utilized; when looking at the open kettle, significantly more heating energy is required to cook the grease. This is in line with previous findings using pilot scale data [1] and what is expected when considering the reduced efficiency of a traditional open kettle in terms of both heat and mass transfer compared to a Contactor reactor.

An additional point that needs to be made is that, of the total energy, approximately 85 percent for both processes is comprised of the heating energy that goes into the system. This can be directly converted to CO_2 emissions, as the amount of fuel is measurable. Any improvement in this production parameter will have significantly greater impact on the reduction of the required energy for the production process, irrespective if an open or a closed production system is used.

6.2 The impact of the base oils on the energy consumption

The essential part of the reduction in energy requirement, when it comes to the paraffinic/naphthenic based grease, comes from the reduction of the thickener content. A higher yield clearly means reduced energy requirement per unit product. Nonetheless, it can be observed that, also, the overall energy requirement in purely naphthenic batches (such as TB02) compared purely paraffinic batches (such as TB03), is lower by about 5 percent when looking at the absolute values.
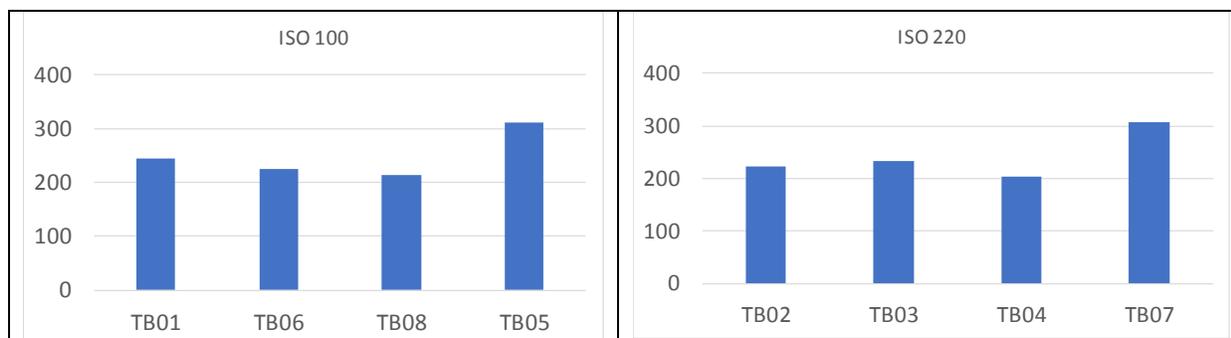

Figure 6.Total Energy requirement per MT of produced grease for TB01 – TB08.

Looking at the results, it is clear that there is significantly more energy required for the test batches produced in the open kettle process. The difference is as high as 33.5 percent for the ISO VG greases 220 and 31.0 percent for the ISO VG 100 greases produced in the open kettle compared to the pressurised vessel.

Also, there is a small advantage when formulating in a higher viscosity base oil, as for three out of four cases the energy required is lower. This is mainly due to the yield benefit. This can be seen in Table 10 where the energy savings is in the region of 5 percent. It is noteworthy that for TB07, a naphthenic/paraffinic blend was used instead of a paraffinic as for TB05. If a fully naphthenic base oil blend was chosen, a bigger difference would probably have been observed based on the other generated data.

Remarks	TB 01 Naphthenic ISO 100	TB 06 Paraffinic ISO 100	TB 08 N/P ISO 100	TB 05 Paraffinic ISO 100
Energy [kWh/MT]	244.53	225.02	214.9	311.65
Batch No.	TB 02 Naphthenic ISO 220	TB 03 Paraffinic ISO 220	TB 04 N/P ISO 220	TB 07 N/P ISO 220
Energy [kWh/MT]	222.94	233.99	204.06	306.7
Energy Saving, [%] ISO 220 vs. ISO 100	9.7	- 3.8	5.3	1.6

Table 10. Energy requirement versus base oil type.

One additional factor to consider is that heating energy losses for the open kettle process are significantly higher than those of the pressurised vessel and, also, the time required is much longer (on average 107

versus 288 minutes). Consequently, the energy required for mixing is also increased (approximately 16.3 kWh in the pressurised vessel versus 21.71 kWh on the open kettle).

Looking at the obtained results, it should be noted that all grease batches produced in an ISO VG 220 base oil blend starting with a high viscosity naphthenic base oil in the cooking stage and then finishing the grease with a lighter naphthenic or paraffinic base oil showed an improved yield. This in turn means that the energy requirement on a kW to kg basis will be lower. This is irrespective of the manufacturing procedure and was found both on the atmospheric and pressurised batches. When formulating the grease on a paraffinic base this was not observed and as a matter of fact there was a small energy penalty for the ISO VG 220 where in terms of the electricity required there was an additional requirement of approximately 4 percent in the cooking stage and 7 percent in the finishing stage.

7. Carbon Footprint

Throughout industrial and commercial applications, the reduction of greenhouse gasses (GHG) is seen as part of corporate responsibility, with many large and small corporations setting targets of becoming carbon neutral in the future. The first step towards this is usually taken by applying a standardized reporting system such as the GHG Protocol [9] which allows the organization to uniformly account for and manage CO_2 and other emissions. This forms part of a greater requirement of sustainability by managing all resources including material, financial and people. The most commonly considered gases are HFC gases, methane, NOx, and carbon dioxide with the latter accounting for approximately 80 percent of the beforementioned emissions on a global scale. Figures provided from the US EPA [15], show that over the past two decades, they have been relatively constant despite the numerous attempts through UN initiatives such as the Paris Agreement in 2015 and the more recent COP24 climate summit in Poland as well as the work done by NGOs.
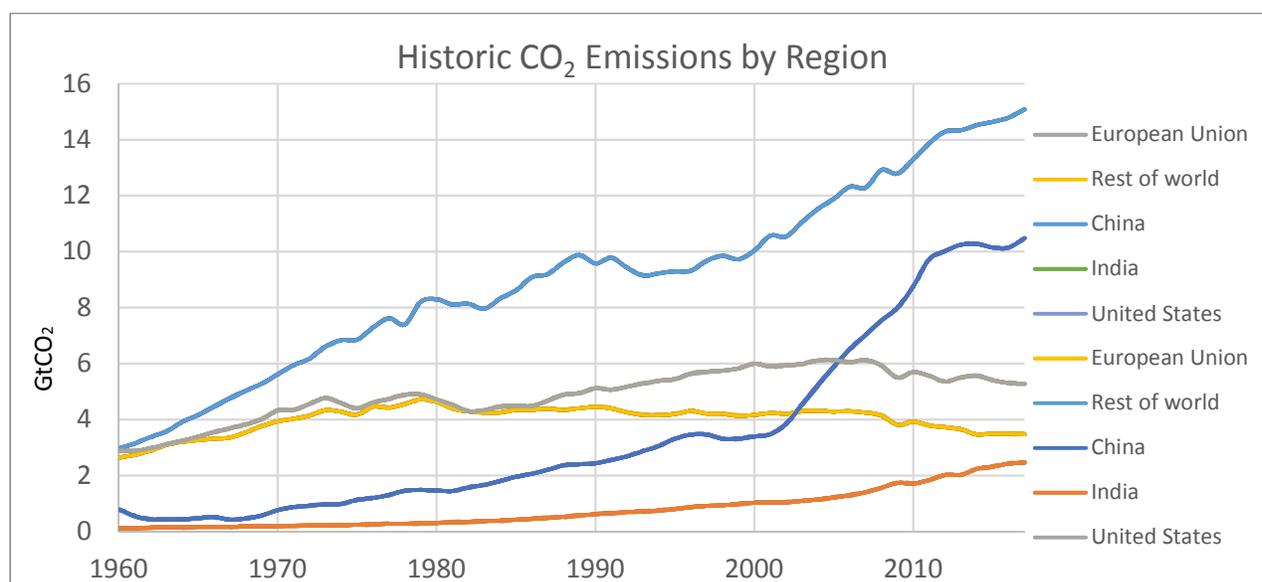

Figure 7. Major contributors to CO_2 global emissions.

In the study conducted, there are two elements that have to be accounted for in the case of grease production: the energy usage in the form of electricity and the energy usage in the form of heating.

There are various tools available to evaluate the carbon footprint of the electricity provided by local utility companies. Today there are utility companies that can provide energy that is produced using exclusively renewable sources. Nonetheless in various global regions, the energy source will vary from coal to nuclear and renewables, such as water, wind and solar. Where renewable sources are used, the overall resulting CO_2 emissions from a given operation can theoretically be zero. More and more countries are moving away from fossil fuel for electricity production [16].

As seen from the results of this study, the electricity consumed during grease production only represents a small amount of the total system energy, ranging from 12% – 16%. The majority of the energy comes from the heating requirements. Currently, apart from small scale operations where the circulating medium can be electrically heated (pilot scale), there are only a few novel processes that use electricity as a means of heating, with the most discussed method being microwave heating for grease production [10]. The supply of high-pressure steam as a utility, where available, presents a unique energy calculation, but, in this case, the source of steam generation also needs to be evaluated.

For fuel fired systems, the CO_2 emissions can easily be accounted for by applying a GHG model [9] applicable for the energy source used by the local utility supplier. For the majority of grease plants, fuel for the heating source is some sort of fossil fuel. This could be Natural gas, LPG, Diesel, a heavier distillate or an alternative fossil fuel derived source. Depending on the region and supplier, these sources can incorporate a sustainability factor, such as, for example, biofuel for diesel.

Fuel	Emissions in [kgCO$_2$ / kWh]	Emissions in [kgCO$_2$ / GJ]
Lignite	0.36	101.2
... Lusatia	0.41	113.0
... Central Germany	0.37	104,0
... Rhineland	0.41	114.0
Hard coal	0.34	94.6
Fuel oil	0.28	77.4
Diesel	0.27	74.1
Crude oil	0.26	73.3
Kerosene	0.26	71.5
Gasoline	0.25	69.3
Refinery gas	0.24	66,7
Liquid petroleum gas	0.23	63.1
Natural gas	0.20	56.1

Table, 11. CO$_2$ emissions per kWh, Source: Fachbuch Regenerative Energiesysteme and UBA.

In order to evaluate the overall carbon footprint of the production stage of the operation considered, the different test batches were compared. The production in the pressurised kettle using a blended naphthenic/paraffinic base stock of ISO 220 (TB 04) was used as a bench mark as this gives the overall lowest results in terms of energy demands.

For LPG, the fuel used, the CO_2 emissions per kWh is give in Table 11.   Also considering the electricity production fuel mix during the batch production period (43% Lignite, 37% Diesel, 12% LNG & 8% Renewable) the average CO_2 emission values can be calculated to give the values in Table 14.

Energy source	CO₂ emissions
Heating	0.23
Electricity	0.28

Table 12. CO_2 Emissions for production batches in kg eCO_2 per kWh.

Batch	Base oil - Type	Viscosity @ 40°C, [mm²/s]	Thickener content, [wt.%]	Cooking Vessel - Type	Kg eCO₂ emissions per MT	Normalised CO₂ emissions per MT
TB 04	Naph/Paraf	220	5.4	Pressurised	48.62	1
TB 02	Naph	220	4.8	Pressurised	53.04	1.091
TB 08	Naph/Paraf	100	7.1	Pressurised	53.38	1.098
TB 06	Paraf	100	8.2	Pressurised	53.44	1.099
TB 03	Paraf	220	7.5	Pressurised	55.58	1.143
TB 01	Naph	100	7.2	Pressurised	57.81	1.189
TB 07	Naph/Paraf	220	7.6	Open	65.75	1.352
TB 05	Paraf	100	8.9	Open	73.62	1.514

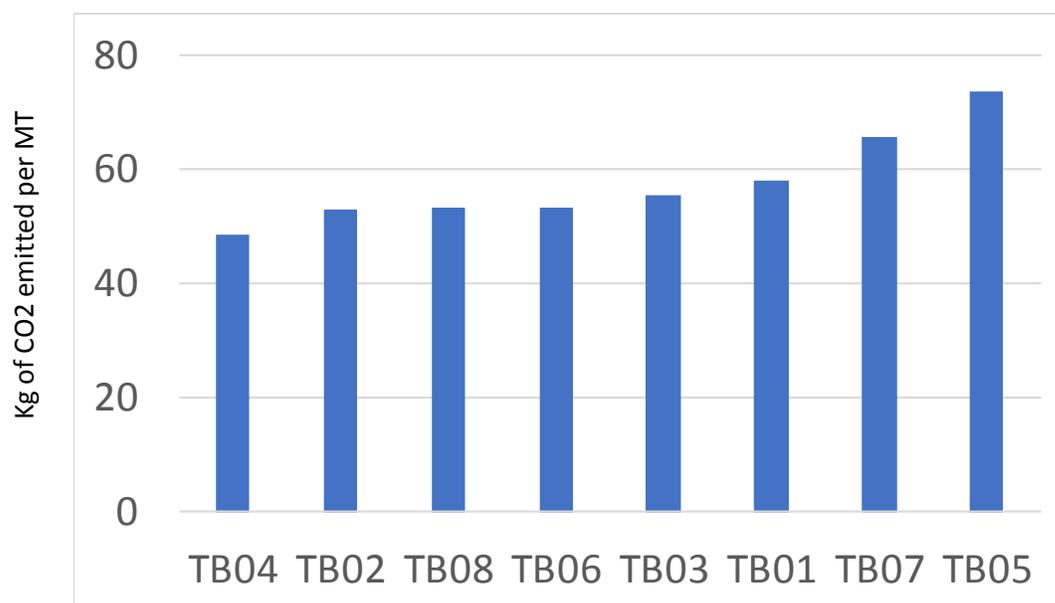Table 13. Normalized CO_2 emissions from production batches.

Figure 8. kg CO_2 emitted per MT of grease produced.

Considering the test batches with the same base oil viscosity, it can be seen that, for the grease with an ISO VG 220 oil, an overall reduction in CO_2 emissions of 35.2 percent can be achieved by switching from a paraffinic base oil in an open kettle to a paraffinic/naphthenic base oil mixture in a pressurised process. Similarly, considering a grease with an ISO VG 100 oil, an overall reduction in CO_2 emissions of 41.6 percent

can be achieved by switching from an open kettle production process using a paraffinic/naphthenic base oil blend to a pressurised vessel using a naphthenic base oil.

Batch	MT CO_2 emissions per 1000 MT Heating	MT CO_2 emissions per 1000 MT Electrical	Combined CO_2 emission reduction potential per 1000 MT grease
TB 04	39.15	9.48	-
TB 02	43.18	9.85	4.41
TB 08	44.10	9.28	4.76
TB 06	44.02	9.41	4.81
TB 03	45.69	9.89	6.96
TB 01	49.02	8.80	9.19
TB 07	53.94	11.82	17.12
TB 05	62.74	10.88	25.00

Table 14. Emission reduction potential of using each batch process by energy stream.

Looking at the absolute per metric ton values for every 1000 MT per year production, the annual reduction of CO_2 emissions between open and closed kettle process is estimated at 18 – 20 MT for paraffinic base oil and up to an additional 5 MT saving if the base oil used is naphthenic. Some CO_2 emission equivalents can be seen in Table 15 below.

CO2 emission saving between TB 04 and TB 05…	Emission offset
…per 8 MT batch	**200 kg CO_2** or 1,800km in a modern EURO 6 passenger car (111 gr. CO_2/km)
…per 80 x 180 kg drums shipped in container	**360 kg CO_2** or Sea freight of container from Rotterdam to Singapore (36 gr. CO_2/Nautical mile)
…per 100 MT produced	**2,500 kg CO_2** or Flying 6 times between Athens to Stockholm return (205 kg CO_2/leg)
…per 1000 MT produced	**25,000 kg CO_2** or 250,000 km travelled by road trucks with company goods (100 gr CO_2/km)

Table 15. Examples of CO_2 saving offset.

Looking at published industry data by a lubricants manufacturer that is a producer of both lubricating oils and greases [11], it can be noted that an average energy consumption of approximately 232 (kWh per metric ton) of produced product is reported. This value includes all activities on a given production location. Noting that the average energy consumption of the grease batches measured is 245.5 (kWh per MT) *only* considering the production process parameters it can be deduced that any optimisation in this type of products (greases) can have a significant impact on a company's sustainability rating. The measured results show that a significant improvement of over 40 percent in some cases can be obtained in what is indisputably the most energy intensive production activity within the lubricants industry.

8. Summary

This study is based on the production of lithium grease on an industrial scale, in which the impact of a number of key parameters, such as the nature and the viscosity of base oils and the production technologies, on the energy consumption and CO_2 emission mass basis of finished grease were evaluated.

In total, eight batches (8000 kg each) of lithium-based grease was manufactured. The selected base oils were two paraffinic group I oils, three hydrotreated naphthenic oils and the blend of paraffinic and naphthenic oils. The viscosities at 40 (°C) were 100 (mm^2/s) and 220 (mm^2/s), since these are the typical grades for multipurpose lithium greases in the industry.

Based on the obtained results in this study, the following conclusions can be made:

1- Considering the test batches with the same base oil viscosity, it can be concluded that, for the grease with an ISO VG 220 oil, an overall reduction in CO_2 emissions of 21,5% per metric ton of produced product can be achieved by switching from a paraffinic base oil in an open kettle to a paraffinic/naphthenic base oil mixture in the Contactor reactor.

2- The essential part of the reduction in energy requirement, when it comes to the paraffinic/naphthenic blend-based grease, comes from the reduction of the thickener content. A higher yield clearly means reduced energy requirement per unit product. Nonetheless, it can be observed that, also, the overall energy requirement in purely naphthenic batches (such as TB 02) and purely paraffinic batches (such as TB 03), is lower by about 5 percent when looking at the absolute values. Looking at the results, it can be clearly seen that there is significantly more energy required for the test batches produced in the open kettle process. The difference is as high as 33.5 percent for the ISO VG 220 greases and 31.0 percent for the ISO VG 100 greases produced in the open kettle compared to the pressurised vessel.

3- Production of lithium-based grease could be optimized by cooking the grease in a pressurised condition (e.g., STRATCO® Contactor™ reactor) in lieu of at atmospheric pressure. This benefit regarding the yield can then be maximized when the viscosity of base oil is increased from 100 (mm^2/s) to 220 (mm^2/s) and naphthenic oils are used.

4- One additional factor to consider is that heating energy losses for the open kettle process are significantly higher than those of the pressurised vessel and, also, the time required is much longer (on average 107 versus 288 minutes). Consequently, the energy required for mixing is also increased, by approximately 15.57 (kWh) in the pressurised vessel and by 21.28 (kWh) in the open kettle.

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