MECHANICAL ACTION IN CO_2 DRY CLEANING

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Abstract. High-pressure carbon dioxide (CO_2) is one of the most suitable replacements for perchloroethylene (PER), a common but harmful textile dry cleaning solvent. Previous studies have indicated that the particulate soil removal with CO_2 is lower compared to that with PER, because of the lesser amount of mechanical action in CO_2. Furthermore, there is a lack of understanding of textile-dirt-CO_2 interaction. It is the objective of this study to get an insight in the (mechanical) forces that play a role in CO_2 dry cleaning and to use this information to improve the CO_2 washing performance. In the experiments, various ways of introducing mechanical action, such as rotating drum, CO_2 spray, ultrasound and bubble formation were investigated. Several types of textiles stained with different kinds of particulate soils were cleaned using 25 l and 90 l CO_2 dry cleaning set-ups. The washing results show that the rotating drum with additives and additional particles gives the highest cleaning performance. However, the use of additional particles is not practical to be applied in industrial-scale dry-cleaning. Thus, liquid CO_2 spray may be a suitable additional mechanism to provide textile movement. An endoscopic camera has been installed in the 25 l set-up to get an insight in the textile movement inside the rotating drum. The results show that no plug formation occurs and the textile movement in CO_2 is sluggish, which means that the mechanical movement of textile in CO_2 dry cleaning does not follow the simplified tumbling-movement model which was developed in a previous study, and the mechanical action is much less than predicted.

Keywords : CO_2 Dry Cleaning, Mechanical Action

1. Introduction

Dry cleaning is a process of soil removal from substrate, in this case garment/textile, which involves a non-aqueous solvent. This process was developed because some types of textile material are damaged by water, e.g. they wrinkle, shrink, etc. The most common solvent used in conventional dry cleaning is perchloroethylene (PER). Despite its good cleaning performance, PER has several drawbacks such as a toxic effect to the human body.

These drawbacks of PER have started the investigations of several alternative solvents for textile dry cleaning, including hydrocarbon solvents, silicon based solvents and carbon dioxide (CO_2) [1]. CO_2 has several advantages compared to the other solvents. It is non-toxic, non-flammable, non-corrosive, safe for the environment, cheap, easily recovered, and available on a large scale. Furthermore, the drying step is not necessary because CO_2 evaporates from the fabrics during the depressurization step.

Previous studies have indicated that the cleaning performance of CO_2 for non-particulate non-polar soil removal is comparable to that of PER. This is because CO_2 is non-polar and thus interacts well with non-polar soil e.g., fat and oil. However, CO_2 removes significantly less particulate soil than PER. This is due to the low density difference between the liquid and the gas phase of CO_2 which leads to a low level of mechanical action in CO_2 dry cleaning [2, 3]. There is also a lack of understanding of textile-dirt-CO_2 interaction.

To fill this gap, this study aims to get an insight in the (mechanical) forces that play a role in CO_2 dry cleaning, and to use this information to improve the CO_2 washing performance for particulate soils. This will be done by conducting washing experiments in pilot-scale dry cleaning set-ups and introducing various mechanical actions, such as rotating drum, CO_2 spray, ultrasound, and bubble formation, in the presence of co-solvent and/or surfactant. The cleaning chamber will contain textile samples soiled with several types of particulate soil. Furthermore, an endoscopic camera has been installed in the 25 l set-up to get an insight in the textile movement inside the rotating drum.

2. Materials and Methods

2.1 25 l Delft set-up

The dry-cleaning experiments were conducted in a CO_2 dry-cleaning set-up at TU Delft, the Netherlands, which is schematically presented in Figure 1. The pilot-scale set-up was designed and constructed at the Laboratory for Process Equipment, TU Delft. The cleaning chamber (Van Steen Apparatenbouw B.V., the Netherlands) has an 0.25 m inside diameter and 25 l volume, is equipped with an inner drum with a diameter of 0.21 m and has a volume of 10 l. The inner-drum, which is perforated and connected to a rotating shaft which is set to rotate at 75 rpm, is used to provide the mechanical action (tumble) as in a regular washing machine. CO_2 was circulated through the closed-loop system by a centrifugal pump. During each cycle (of circulation), CO_2 passed through a heat exchanger. The detailed procedure of the washing experiment has been described in a previous publication [4].

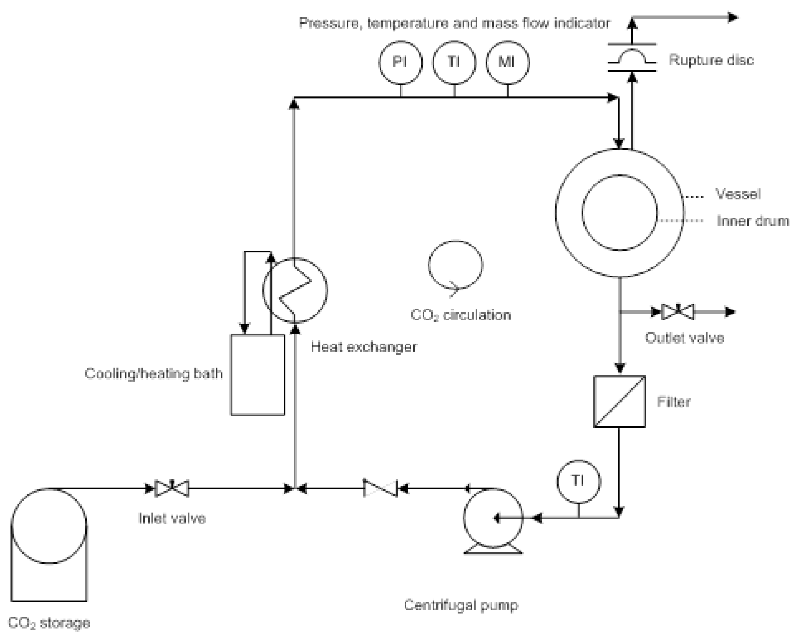

Figure 1. Schematic representation of 25 l Delft dry-cleaning set-up

Fifteen pieces of soiled test fabric of 6.5 x 7.5 cm^2 (Center for Testmaterials B.V., the Netherlands) were used in each washing experiment. They consist of three types of textile -cotton, polyester or wool-, each stained with one type of particulate soil -clay, sebum colored with carbon black, sand, lipstick, or dust-. These monitors were fabricated as such that each piece of the same type contains a similar soil load. Along with the monitors, cotton filling materials of 25 x 25 cm^2 were added into the cleaning chamber to reach the desired washing load of 400 g. Six kg of CO_2 grade 2.7 (Linde Gas Benelux B.V., the Netherlands) was used in each washing and rinsing step. Several additives were used in the experiments: 10 g Amihope LL (Ajinomoto Co. Inc., Japan) as surfactant, 250 g 2-Propanol (IPA) with a stated purity >98% (Prolabo, the Netherlands) and 25 g tap water as co-solvents, as well as 10 g 200µm sand as additional particles to enhance the mechanical action (Filcom B.V., the Netherlands). All given data are average values based on two or more replications for each experiment. To monitor the cleaning results, the color of the fabric was measured before and after washing with a spectrophotometer Data Color 110. The detailed procedure has been described in a previous study [5].

2.2 1 l Unilever set-up

A dry-cleaning set-up containing a high pressure cell was used for washing soiled monitors in CO_2 (see Figure 2). The cell is equipped with a hollow wall which is connected to a cooling/heating bath. The cell has a diameter of 8 cm, length of 25 cm and 1 l working volume. The set-up was developed by Unilever (Vlaardingen, The Netherlands). The washing time was fixed to 1 hour. The temperature (12^{o}C) and the pressure (47 bar) of the system were regulated with a cooling/heating bath. Mechanical action has been provided to the system with 1) regulating the process temperature (*bubbling*) or by 2) decreasing the local pressure with a) rotating stirrer with maximum velocity of 60 rpm or b) an ultrasound transducer at the bottom of the cell (optimum frequency 24.5 kHz; power output of amplifier 180 W). The detailed procedure has been described in a previous publication [6].

Soiled test fabric (4 x 4 cm^2) was used in the washing experiments. These monitors were purchased from WFK (Germany) and fabricated with a spraying method as such that each piece contains a similar soil load. A mixture of motor oil with soot on four different types of textiles (cotton, polyester, polyester/cotton 65/35 (polycotton), and wool) were washed in CO_2. CO_2 grade 3.7 was purchased from Linde Gas Benelux B.V. (the Netherlands). In each experimental run 0.72 l of liquid CO_2 was used. After cleaning, both fabric samples were characterized in respect to their cleanability and soiling degree due to soil re-deposition during the cleaning process with SAD method [6].

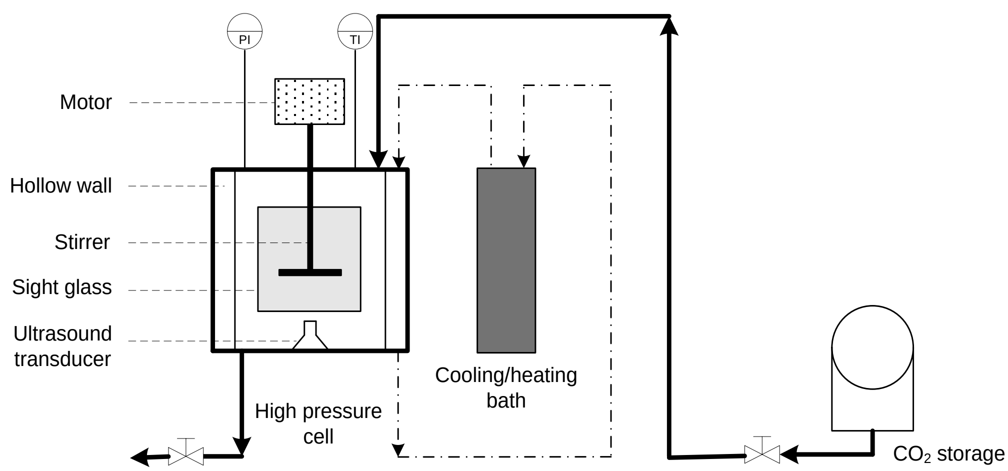

Figure 2. Schematic diagram of 1 l Unilever CO_2 dry-cleaning set-up

2.3 90 l Amsonic set-up

A prototype of an economic liquid CO_2-plant (elCO_2) from Amsonic Precision Cleaning AG/SA was used for textile cleaning. The set-up was operated with liquid CO_2 at a temperature of 15-20°C and a pressure of 51-57 bar. The 90 l cleaning chamber (autoclave) contained a washing basket. The mechanical action upon the textile material was provided by three different mechanisms: 1) gaseous CO_2 flow through several holes that were located above and below the autoclave or 2) an integrated ultrasonic transducer or 3) liquid CO_2 flow (Figure 3). The set-up was equipped with a CO_2 compressor, and a series of filters between 25 µm and 1 µm to remove particles from CO_2 flow. The drawing of this set-up which is located at IPK Fraunhofer, Germany, and a detailed procedure have been described in a previous study [7]. The textile material and analytical methods used in the washing experiments are similar as in 25 l Delft set-up. The CO_2 level was set to 2/3 of the height of the autoclave and 10 ml of ClipCOO (Kreussler, Germany) was used as surfactant.

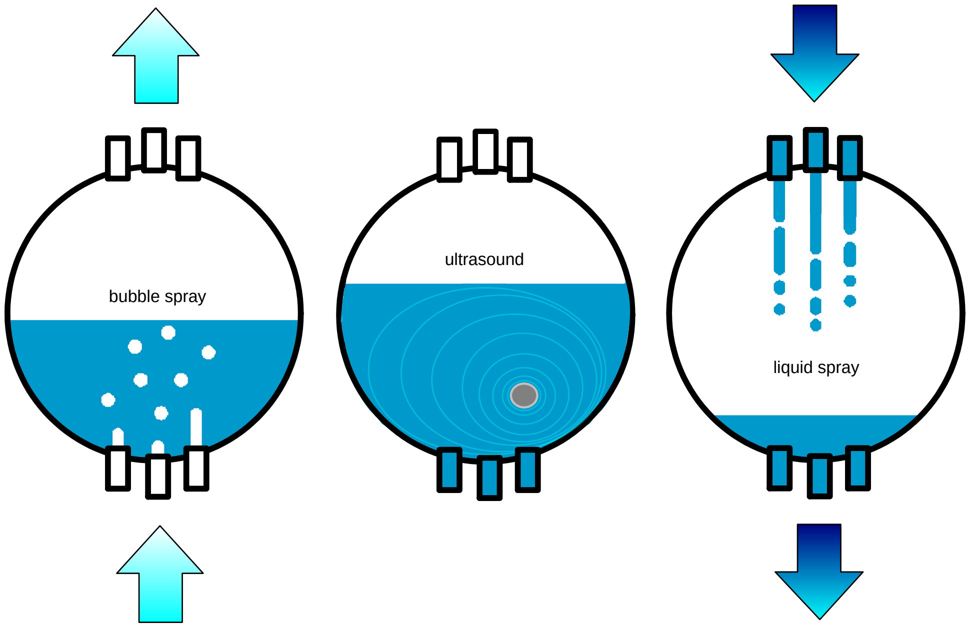

Figure 3. Schematic illustration of the mechanical actions in 90 l Amsonic set-up

3. Results and Discussion

3.1 Mechanical actions in CO_2 dry cleaning

In this study, various mechanical actions have been investigated in 3 different set-ups. These mechanical actions are:

- Rotating drum (25 l Delft set-up)
- Additional particles (25 l Delft set-up)
- Bubbling (1 l Unilever set-up)
- Stirrer (1 l Unilever set-up)
- Ultrasound (1 l Unilever set-up and 90 l Amsonic set-up)
- Bubble spray (90 l Amsonic set-up)
- Liquid spray (90 l Amsonic set-up)

A rotating drum as in the 25 l Delft set-up is most commonly used in commercial dry cleaning machines to provide the mechanical action. In general, the washing performance is acceptable for non-polar soils but resulting in unsufficient particulate soil removal. From the experiments conducted in the 25 l set-up, it was found that in most cases, using only CO_2 in a rotating drum increases the soil removal compared to when no additional mechanical or chemical action is used (only CO_2 in non-rotating drum). Using additives (solid surfactant particles and co-solvents) in most cases further increases the washing performance and using additional particles like sand in the rotating drum, gives for some cases a further increase of average CPI with 67%. The results are presented in Figure 4.

The 1 l Unilever set-up at University of Twente has three different actions: bubbling, stirring, and ultrasound. The cleaning performance with three different actions are given in Figure 5 and the redeposition level in Figure 6. Bubbling is bubble formation due to the temperature difference because the cooling jacket in this set-up does not reach the top of the cell (see [6] for a more elaborate explanation). For particulate soil removal (motor oil), bubbling and ultrasound both give better washing results (lower redeposition level and higher cleaning performance) than stirring. Stirring induced high turbulence and thus high redeposition level because the set-up is not equipped with circulation or filter to remove the dislodged soil. However, the high redeposition level shows that many particles have been dislodged from the textile. In bubbling and ultrasound, the particulate soil has a bigger chance to settle on the bottom of the cell due to gravitational force. Because of the way the equipment is built and the high redeposition levels, it cannot be concluded which is the best way to remove particles from the textile. Furthermore, these results cannot directly be compared to the results in the 25 l set-up because of a significant difference in various process conditions such as the types of soil, etc.

Experiments to test different kinds of mechanical action were also conducted in a 90 l Amsonic set-up at IPK Fraunhofer. This set-up is equipped with three different actions: ultrasound, bubble spray, and liquid spray. The results are shown in Figure 7. It appears that among these actions, liquid spray for most cases shows the highest cleaning performance. However, the overall influence of all three sources of mechanical action on the cleaning results is small.

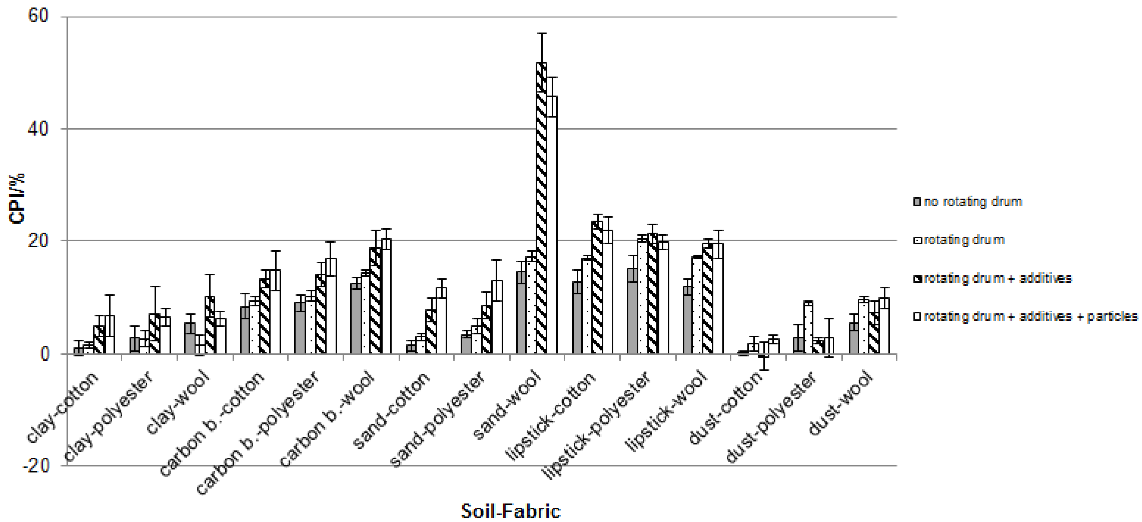

Figure 4. Cleaning Performance Index in 25 l Delft set-up

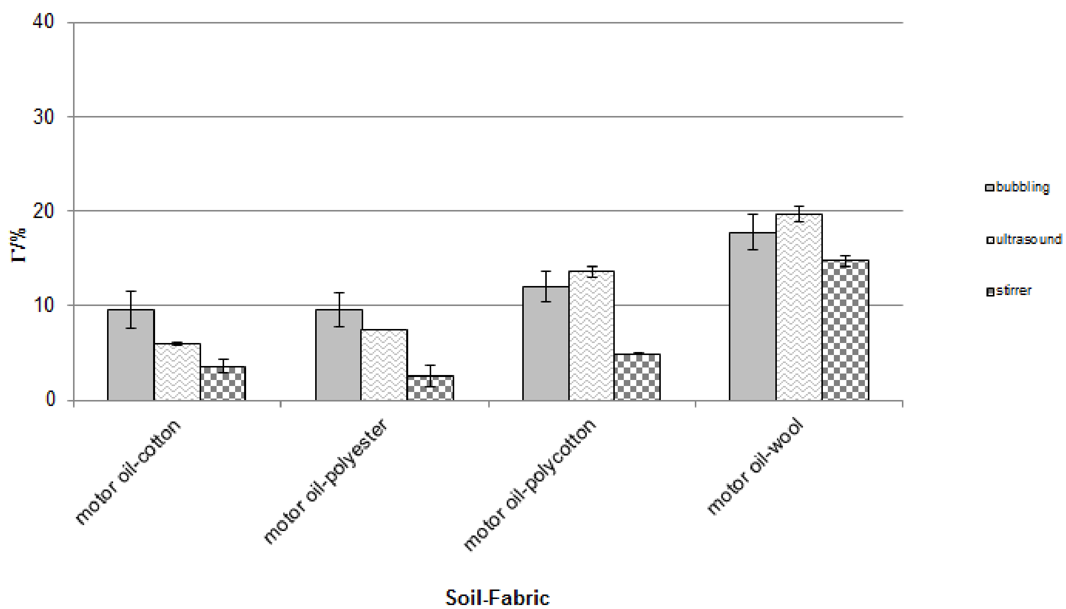

Figure 5. Cleanability in 1 l Unilever set-up

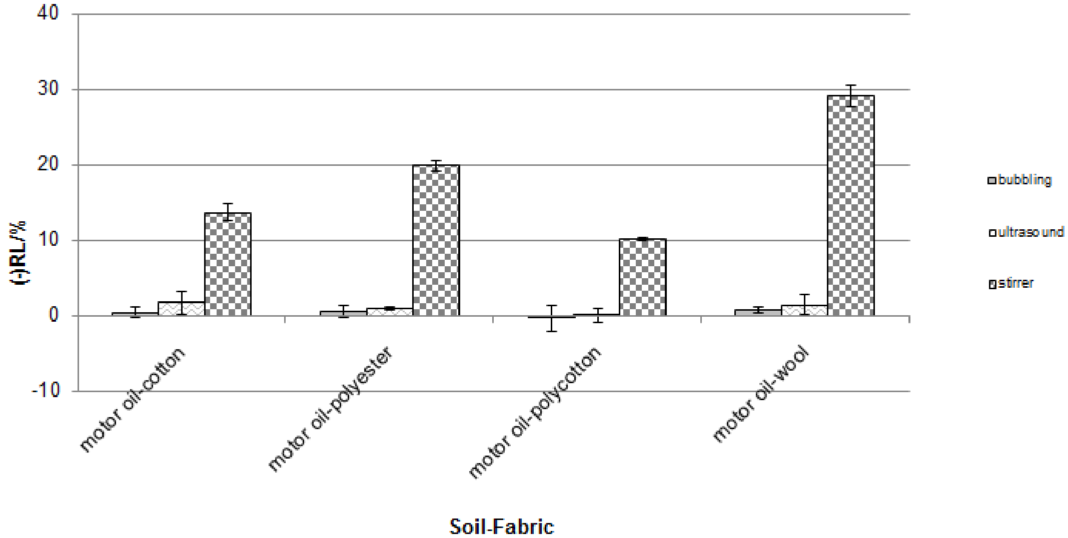

Figure 6. Redeposition level in 1 l Unilever set-up

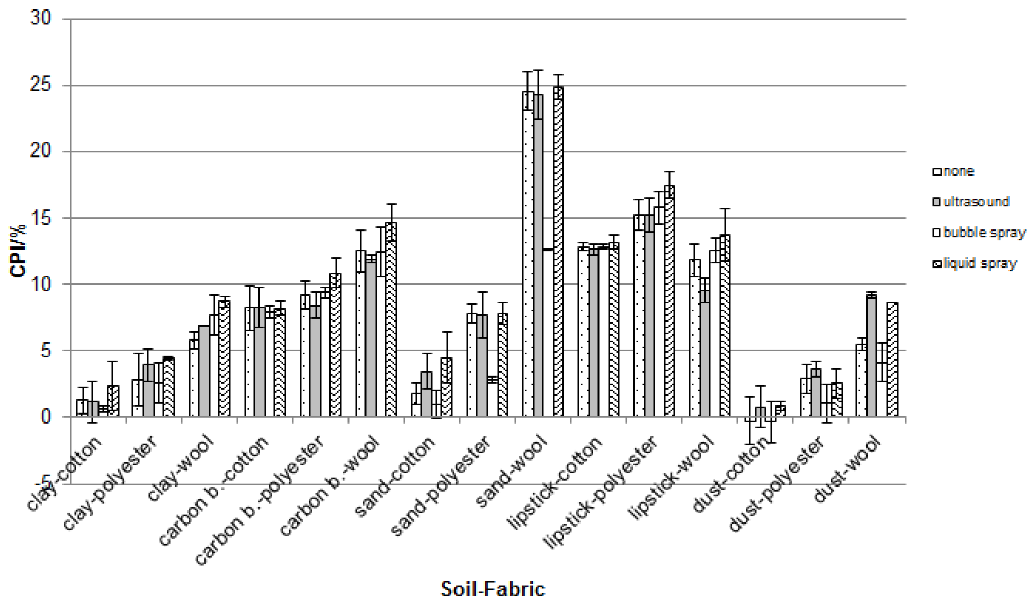

Figure 7. Cleaning Performance Index in 90 l Amsonic set-up

3.2 Textile movement in a rotating drum

An endoscopic camera has been installed in the 25 l set-up at TU Delft to get an insight in the textile movement inside a rotating drum (see Figure 8). The following process parameters were varied and the effect on the textile movement was studied:

- Degree of textile filling
- Amount of CO_2
- Process temperature and pressure under supercritical conditions, no visual image is available because the light source is not transmitted through the supercritical phase.
- Pump circulation rate

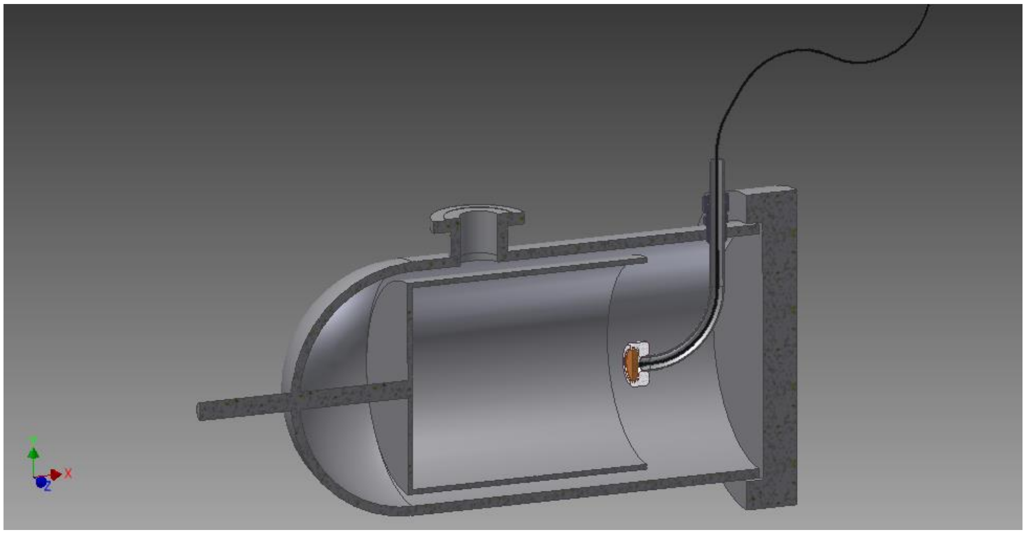

Figure 8. Endoscopic camera installation inside 25 l Delft set-up with rotating drum

An example of a picture shot taken during the observation is given in Figure 9. Using the video camera, it has been observed that the textile movement in CO_2 is sluggish (i.e. it does not rotate as fast as the speed of the drum), which means the mechanical action is much less than the one that was predicted.

In addition, no plug formation occurs. This means that the simplified mechanical movement of textile in CO_2 dry cleaning does not follow the tumbling-movement model which was developed in a previous study [5]. This model was based on water-based washing-machine by Van den Brekel [8], where the textile was assumed to be a cylinder plug with diameter and length of 5 cm. The shape of textile in CO_2 (which is not ideal to make the tumbling movement) might contribute to the low amount of mechanical action in the washing process.

When the higher filling degree (8 pieces of textile) was used, the textile moved slightly slower, which implies a lesser amount of mechanical action. The model implied that 10-11 o'clock for left rotation and 1-2 o'clock for right rotation are desirable as the drop-off point of the textile. On several cases, when using a high degree of filling, it was observed that the textile was stuck in a certain position and did not rotate along with the drum until the rotation direction was changed or that the textile rotates along with the drum without the falling action or fell before reaching the desired point. Without the falling and hitting-the-wall movements, the mechanical action in CO_2 dry cleaning is reduced significantly, resulting in low cleaning performance.

The amount of CO_2 affects the liquid CO_2 level inside the rotating drum and thus determines whether the fallen textile will hit the wall (desirable) or hit the liquid. When the amount of CO_2 was increased to 10 kg, the liquid CO_2 level reached the middle of the rotating drum (while 6 kg of CO_2 only reached the bottom of the drum). It was observed that the movement of textile was more sluggish in 10 kg than in 6 kg of CO_2 which indicates that the mechanical action in 10 kg of CO_2 is lower than in 6 kg.

The process temperature affects the density difference between liquid and gaseous CO_2. It is expected that the lessened density difference between liquid and gaseous CO_2 at higher temperature results in higher drag force and lower net gravitational force, and thus lower terminal velocity and lower mechanical action [5]. However, when a higher temperature (25^{o}C) was used instead of 10^{o}C, no significant difference in the speed of textile movement was observed, however the liquid CO_2 level was less than the one in 10^{o}C.

The pump circulation rate could act as a liquid CO_2 spray that stimulates the textile movement. By using the video camera, it has been observed that the textile movement can be significantly enhanced by CO_2 circulation with a pump, liquid CO_2 flow that was circulated by the pump at 500 kg/h created a turbulent flow of CO_2 inside the cleaning vessel, which increases the textile movement and thus increases the amount of mechanical action in the washing process. The observation supports the results from the previous section that a liquid CO_2 flow (i.e. liquid spray) stimulates textile movement. These results will be used to modify the model of textile movement in CO_2 inside a rotating drum which was developed in a previous study.

Figure 9. Textile movement inside a rotating drum for 1 piece of textile, rotation speed: 75 rpm, rotation direction: right-left, amount of CO_2: 6 kg, T: 10^{o}C, no pump circulation, no baffle

4. Conclusion

The washing results show that the rotating drum with additives and additional particles gives the highest cleaning performance. However, the use of additional particles is not practical to be applied in industrial-scale dry-cleaning. Liquid CO_2 spray may be a suitable additional mechanism to provide textile movement. The observation with video camera shows that no plug formation occurs and the textile movement in CO_2 is sluggish, which means that the mechanical movement of textile in CO_2 dry cleaning does not follow the tumbling-movement model which was developed in a previous study and the mechanical action is much less than the one that was predicted.

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References

[1] http://www.arb.ca.gov/toxics/dryclean/alternativesolvts_e.pdf
[2] B. Gosolitis, J. Kurz, M. Sverev, Textile dry-cleaning in liquefied CO_2, Proceedings of the Second International Meeting on High Pressure Chemical Engineering, Hamburg, Germany, 2001.
[3] M.J.E. Van Roosmalen, G.F. Woerlee, G.J. Witkamp, Dry-cleaning with high pressure carbon dioxide, experimental set-up and washing-results, Proceedings of the Second International Meeting on High Pressure Chemical Engineering, Hamburg, Germany, 2001.
[4] S. Sutanto, M.J.E. Van Roosmalen, G.J. Witkamp, Redeposition in textile dry-cleaning with carbon dioxide, Proceedings of 13th European Meeting on Supercritical Fluids, Den Haag, Netherlands, 2011.
[5] M.J.E. Van Roosmalen, PhD Thesis, Dry-cleaning with high-pressure carbon dioxide, 2003, Netherlands.
[6] S. Sutanto, V. Dutschk, M.J.E. Van Roosmalen, G.J. Witkamp, Performance of CO_2 Dry-cleaning with Cavitation, Proceedings of 10th International Symposium on Supercritical Fluids, San Francisco, USA, 2012.
[7] S. Kareth, M. Bilz, J. Mankiewicz, M. Petermann, D. Rebien, M. Wehrl, Compressed carbon dioxide – a green washing fluid for medical parts, Proceedings of 10th International Symposium on Supercritical Fluids, San Francisco, USA, 2012.
[8] L.D.M. van den Brekel, PhD Thesis, Hydrodynamics and Mass Transfer in Domestic Drum- Type Fabric Washing Machines, 1987, Netherlands.