Cambridge Short Research Visit

Visit Dates: 5th – 17th November 2017

Location: Department of Chemical Engineering & Biotechnology, University of Cambridge, Philippa Fawcett Drive, Cambridge CB3 0AS

Attendee: Alistair Rodgers

University of Cambridge Contacts: Professor Ian Wilson, Rajesh Bhagat

1. Introduction

The purpose of the research visit was to collaborate with Prof Ian Wilson and Rajesh Bhagat of the University of Cambridge, who have been doing research in to the same area of cleaning using liquid jets. Contact had been established with Prof Wilson at the Special Interest Group (SIG) meetings of The UK Fluids Network (UKFN) in the fluid mechanics of cleaning and decontamination. The similarities in research with Prof Wilson were highlighted at the SIG meetings and after discussion the idea of a research visit seemed beneficial. This was due to Prof Wilson having access to equipment that was not available in Leeds and that would provide useful data for the project. Firstly a confocal thickness sensor (CTS) was accessible in Cambridge, which was used to scan a surface that had been cleaned to show the distribution and size of the residual film left on the surface. This was particularly useful for the work on sprays, in which very thin residual films remain on the surface after cleaning and are hard to quantify without such equipment. Secondly the test rig set up by Prof Wilson and Rajesh included a mechanism that could move the target plate impinged on by the jet, simulating a dynamic jet. This was of particular interest to the jet work conducted in Leeds and would provide a useful comparison of the mechanisms of soil removal between a static and dynamic jet.

The research visit was funded by UKFN, who encourage communication and collaboration between their members. The total cost of the visit; including travel, accommodation and general living costs, amounted to just under £500. This was well under the budget set by UKFN of £1000.

2. Method

The materials used, as in Leeds, were white soft paraffin (WSP) as the soil and Perspex as the target plate. All experiments were conducted on the test rig set up in Cambridge, which is shown in Fig. 2.1. The rig consisted of a Perspex sheet fixed on to a track on which it could move up and down at varying speeds, controlled by a motor fixed above the rig. In front of the target plate the nozzle was positioned on a frame, on which its height, distance from the plate and angle could be adjusted accordingly. The flow rate could be altered using

Fig. 2.1: Experimental rig

a rotameter fixed to the side of the rig. Water was collected in a drainage system that was recycled in to the flow and the tank was emptied at regular intervals to ensure minimal contamination of the water.

WSP was applied to the plate to a desired thickness, using feeler gauges of specific thicknesses. The WSP was then combed on to the surface to this thickness as shown in Fig. 2.2.

The CTS focused a polychromatic white light on to the target and a specific distance to the target was assigned to each wavelength via a factory calibration. This was used for the spray experiments by calibrating the distance to the cleaned surface, and any deviation from that distance represented the thickness of the film present. In order for the CTS to scan the surface, the sensor was fixed on a clamp that was positioned above an X-Y stepper motor table. The sample was then mounted on to this table which then moved so that the entire surface was scanned. The size of the scanned region and the step size were inputted by the user in to a Python code that thereafter controlled the movement of the table. Due to limitations on the movement of the table, the sample size was restricted and therefore a different target plate was used to the one shown in Fig. 2.1. The table size was 15 x 15cm and so several target plates were cut to this size so that they could be easily mounted on to the table. Fig. 2.3a and 2.3b show said plate on the test rig and mounted on to the table for CTS analysis. Note that before each sample was loaded on to the CTS table, it was first dried out to avoid any noise in the results from water droplets. Spray experiments were conducted for a total of 45 minutes, taking CTS scans of the surface at regular time intervals in order to observe the progression of the cleaned region and the

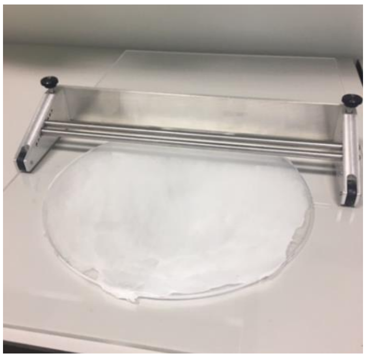


Fig. 2.2: WSP application technique

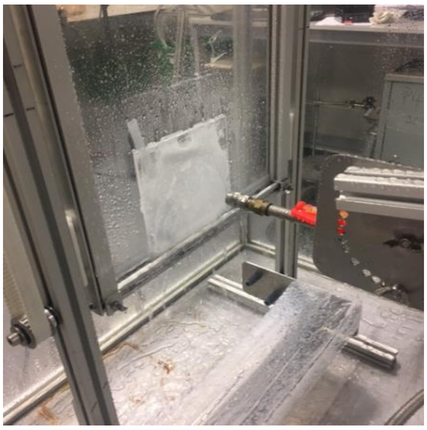
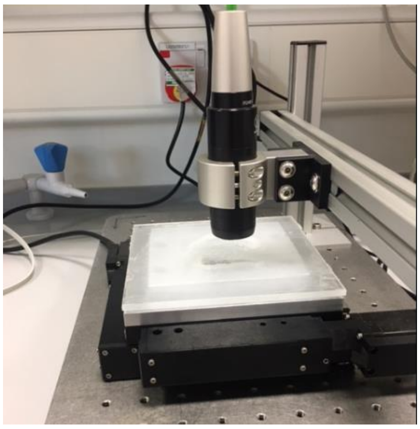


Fig. 2.3a: Sample plate on test rig



2.3b: Sample plate mounted on to X-Y table behaviour of the residual film with time, in order to understand in greater detail the mechanisms of soil removal using the spray.

3. Results & Discussion

3.1 Spray results

Spray experiments as aforementioned were conducted at varying time intervals running up to a total of 45 minutes. After 5 minutes cleaning, the cleaned sample is shown in Fig. 3.1a, whilst the results of the CTS scan are shown in Fig. 3.1b. Note that spray results presented in this section are for a 4l/min spray, 50mm standoff distance of the nozzle and a 1mm film of WSP.

Fig 3.1a: 5 minutes cleaning sample

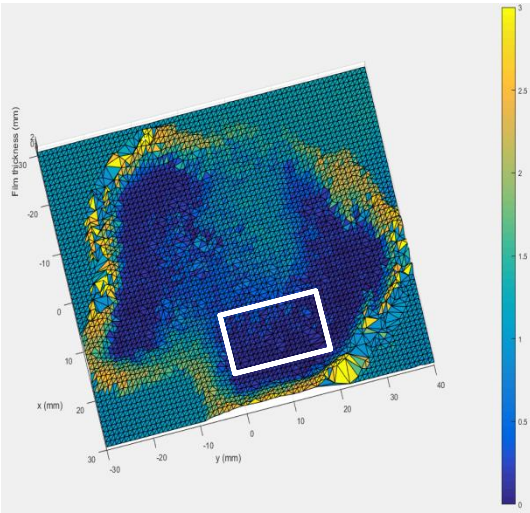


Fig. 3.1b: 5 minutes cleaning CTS

Firstly it can be observed that the CTS scan provides a very good agreement with the cleaned sample, showing many of the same features as the sample in 3.1a. The shape of the cleaned area matches and the uncleaned area in the centre is much the same shape. The ridge of WSP formed on the perimeter is shown by the regions of yellow, corresponding to a maximum thickness of 3mm as shown by the colour bar in Fig. 3.1b. This is where the bulk of the WSP has been forced outwards from the impingement area of the spray and accumulated in to the ridge as was observed in the case of the jet. Note that there are areas in the ridge that show a lower resolution of data points, this is due to the fact that in particular areas of the ridge the light produced by the CTS became out of focus, since it had been calibrated to the surface of the Perspex. As such the CTS produced noisy data points which were removed when processing the data, thus the areas of low resolution. However the characteristics of the ridge are still well represented. It is clear that the central area of the cleaned region has been virtually unremoved, as the colour corresponds to that of the uncleaned area outside of the ridge. The areas closer to the perimeter and to the ridge appear to be far cleaner as they are represented by areas of blue in Fig. 3.1b. However when looking at 3.1a it is clear that this is not in fact fully clean and there is an obvious residual film still present on the surface. By increasing the resolution of the colour bar and zooming in on the region enclosed by the white square in Fig. 3.1b, it can be seen in more detail the characteristics of the residual film. This is shown in Fig. 3.2.

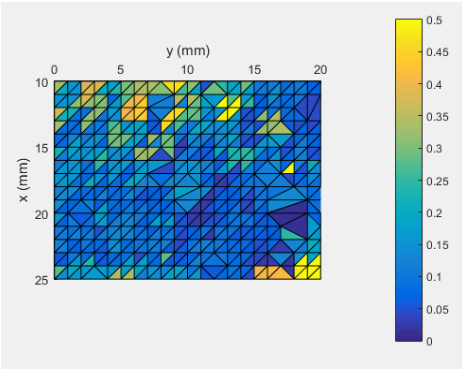


Fig. 3.2: Close-up of highlighted region

Despite the region highlighted in Fig. 3.1b appearing almost fully clean, as it is shown as blue on the larger colour scale, when increasing the resolution of the scale and looking at thicknesses from 0-0.5mm, the extent of the residual film becomes more apparent. Very few pixels are fully clean in Fig. 3.2 and there is largely a residual film of approximately 0.1-0.2mm left on the surface. There are also peaks of up to 0.5mm in this region.

A new sample was created, and it was then cleaned using the spray under the same conditions but for 15 minutes. The resulting cleaned sample and CTS scan results are shown in Fig 3.3a and 3.3b respectively.

Fig. 3.3a: 15 minutes cleaning sample

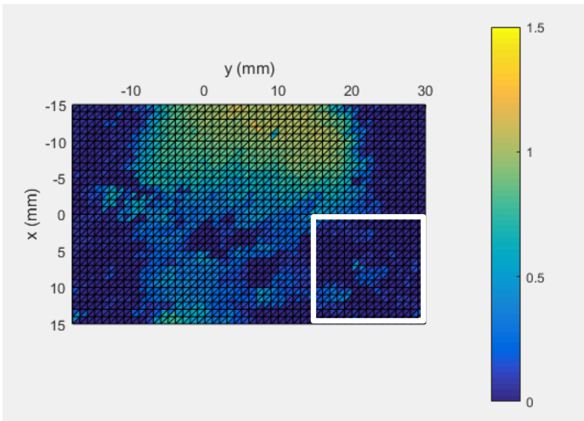


Fig 3.3b: 15 minutes cleaning CTS scan

In this case the CTS scan was focused inside the cleaned region as this was of primary interest. The ridge had already been presented in the 5 minute case and the ridge does not change much with time in the case of the spray. The close-up also gives a better resolution and more detail of the residual film. Note that the cleaned region appears different to the case in 3.1a; this is simply due to the fact that the orientation of the nozzle was slightly different and the same shape in 3.1a has simply been rotated in this case. When looking at the central region it can be observed that again the CTS provides good agreement with what can be seen from the sample. When looking at the case in 3.1b after 5 minutes, there are much more clean areas of blue in Fig. 3.3b after 15 minutes. This can be confirmed when looking at 3.3a as there are clearly more areas of transparency on the surface. The spray has started to remove the WSP more effectively after prolonged contact with the substrate. There is however still a large area of WSP in the centre that appears to remain uncleaned, albeit slightly reduced in size compared to the 5 minute case.

By repeating the same process as the 5 minute case and zooming in on the region highlighted in Fig. 3.3b, the residual film can be viewed in more detail to see how clean the areas of blue really are. This is shown in Fig. 3.4.

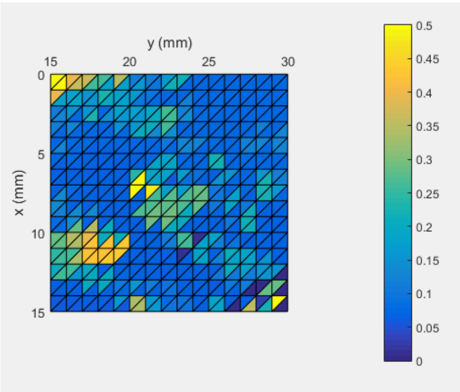


Fig. 3.4: Close-up of highlighted region

Again by looking at a section of the surface that would appear clean on a greater colour scale, by increasing the resolution it becomes clear that it is not in fact clean but the surface is still mostly covered by a residual film. There are very few pixels in 3.4 that have an absolute zero value and the majority of the region is covered by a film of approximately 0.1mm.

Another sample was then cleaned for 30 minutes and the results are shown in Fig 3.5a and Fig. 3.5b.

Fig. 3.5a: 30 minutes cleaning sample

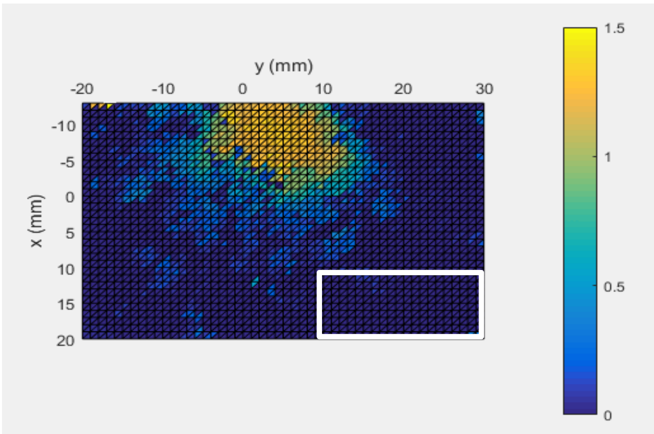


Fig. 3.5b: 30 minutes cleaning CTS scan

Fig. 3.5a and 3.5b show that after a further 15 minutes cleaning, the residual film on the surface becomes less apparent. In Fig. 3.5a there is a large area of transparency on the surface that to the naked eye appears clean. Once again the CTS shows an accurate representation of the surface and there are large areas of deep blue that represent no residual film present. There is, as in previous cases, still an area in the centre of the cleaned region where there exists part of the layer that has not been removed in the slightest. This is smaller in surface area in this case, but the colour bar would suggest that in this case it is actually slightly thicker than in the 15 minute case. This implies that some material has actually been shifted to the centre, as in places the film thickness is higher than the original film thickness of 1mm. This however could also be due to an irregularity in the application of the film. The region highlighted in 3.5b is shown to a higher resolution in Fig. 3.6.

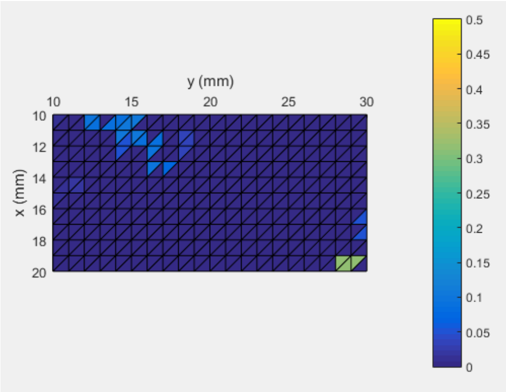


Fig. 3.6: Close-up of highlighted region

In this case the higher resolution image of the surface shows that the surface is genuinely clean in the regions of blue shown in Fig. 3.5b. Fig. 3.6 shows that the vast portion of the area highlighted has a zero film thickness, with a low number of pixels containing any residual film at all. Prolonged exposure to the spray has removed the majority of the material in this region.

Finally the spray was then ran for 45 minutes, the results of which are shown in Fig. 3.7a and 3.7b.

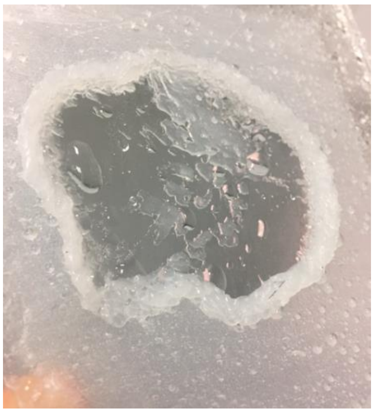


Fig. 3.7a: 45 minutes cleaning sample

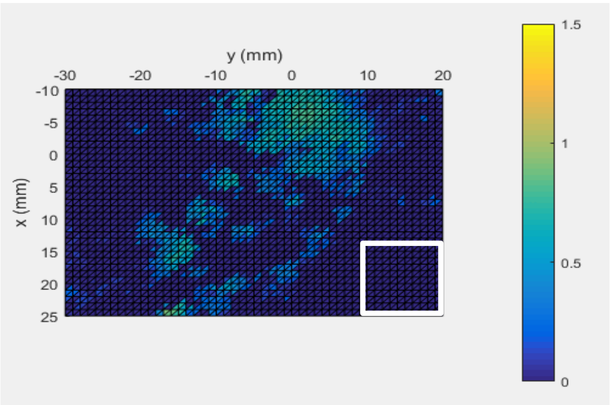


Fig. 3.7b: 45 minutes CTS scan

After 45 minutes cleaning, the sample again shows large areas of transparency in 3.7a and large regions of zero film thickness according to the CTS scan. There is again an area of uncleaned WSP in the centre, which in this case appears less thick than the surrounding film unlike the case of the 30 minutes cleaning sample. This would suggest that the mechanism of soil being pushed in to the centre and accumulating to a greater thickness was an anomaly and more likely due to an irregularity in the application of the film. The higher resolution image of the surface is shown in Fig. 3.8.

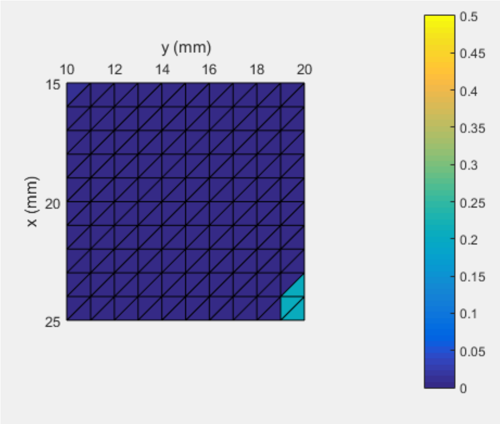


Fig. 3.8: Close-up of highlighted region

Fig. 3.8 shows that after 45 minutes cleaning the spray has removed the vast majority of material in areas that appear clean. Only 3 pixels in the image contain any residual film. The CTS is capable of detecting films on a nanometre scale, so the resolution could be further increased. However from this resolution the film thickness is shown to be less than 0.05mm which can be considered negligible.

The spray experiments have shown that after 45 minutes cleaning there is still the presence of a residual film in the centre of the cleaned region. Fig. 3.9a and Fig. 3.9b show the spray on a clean surface and soiled surface respectively.

Fig. 3.9a: Spray on clean surface

Fig. 3.9b: Spray on soiled surface

The spray on the clean surface (Fig. 3.9a) shows how the film jump created by the spray occurs outside the impinging cone of the spray. The fluid between the cone and the film jump shears the surface and shows the same characteristics of the jet in this region. Soil removal is adhesive in this region whereby the material is peeled off by the shear force exerted on the substrate. When looking at 3.9b, this region occurs inside the ridge and this is the location of the cleaner areas of low residual film thickness shown previously in the CTS scans as areas of blue. Inside the cone a different mechanism of soil removal occurs, the removal is cohesive, the WSP layer is steadily broken down by prolonged contact with the fluid as soaking occurs. Cleaning is less efficient in this region and is the main source of the residual material on the surface. The mechanism of cohesive removal inside the cone remains of interest.

3.2 Dynamic jet results

The dynamic jet experiments were run for two different dynamic jet velocities and two different film thicknesses. The velocities of the moving plate were 2.9cms^{-1} and -13cms^{-1}, where negative velocity indicates the relative motion of the jet to the surface is acting downwards. Note that the jet actually remains static and it is the plate that moves, but velocities will be referred to as moving jets for simplicity. The film thicknesses were set to 0.2mm and 1mm. The flow rate of the impinging jet remained constant at 2.5l/min. The 2.9cms^{-1} plate and 0.2mm film results are shown in Fig. 3.10.

Fig. 3.10: Clean area for 0.2mm film, 2.9cms^{-1} moving jet

The clean area in Fig. 3.10 shows similar characteristics to that observed in the case of the static jet. The formation of the ridge of WSP at the perimeter of the clean area can be observed. In this case the ridge at the frontier of the clean area is ploughed through the uncleaned material as the plate moves downwards. The path of the jet leaves a distinct trail of noticeably cleaner Perspex where it appears more transparent and there is a more clouded, relatively soiled area of Perspex between this trail and the ridge. This can be seen more clearly in Fig. 3.11. The falling film can be seen far below the impingement point of the jet. The ridge of WSP has formed a channel for the falling film and it is very narrow compared to the same flow conditions as the static jet. Further downstream of the impingement point, where the film flow has developed, a very narrow stream is formed.

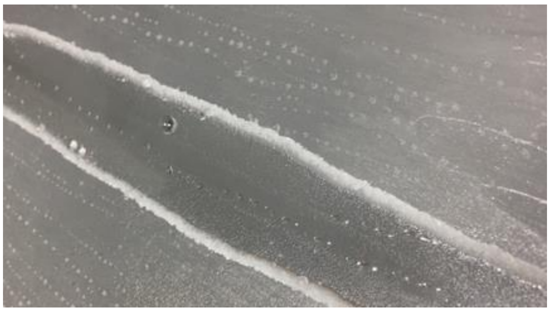


Fig. 3.11: Close-up of jet trail

The area cleaned in the wake of the impinging jet still contains a very thin residual film between the trail of the jet and the ridge of WSP. Due to the lack of contact time as the jet moves across the surface the diameter of the cleaned region does not have time to reach that of the film jump for a given flow rate. The WSP on the surface restricts the fluid reaching the film jump radius and the jet is not in contact with a particular point on the surface long enough to reach it.

For the same film thickness, 0.2mm, but a faster moving jet of $-13cms^{-1}$ the resulting clean area is shown in Fig. 3.12. In this case the contact time with the jet and each point on the surface is considerably shorter and as a result the time for clean area growth is much shorter. The diameter of the clean area in wake of the jet is approximately that of the impinging jet and a very thin trail is left behind. The ridge of WSP formed is also noticeably smaller in volume than the case of the slower moving jet. Since in this case the jet is moving downwards relative to the surface, the falling film forms above the impingement point of the jet and is channelled upwards by the ridge.

Fig. 3.12: 0.2mm film, $-13cms^{-1}$ moving jet

When increasing the film thickness to 1mm, the clean area produced by the $2.9cms^{-1}$ plate is shown in Fig. 3.13. The clean area produced resembles closely that of the same velocity plate but the 0.2mm film shown in Fig. 3.10. However in this case the ridge formed is greater in size due to more material being transported. As a result, as the ridge ploughs through the uncleaned material as the jet moves upwards relative to the surface, the ridge begins to fragment and peel off, leaving waves of material detaching from the surface which can be viewed more clearly in Fig. 3.14. The material can be seen to break off in regular intervals and as previously mentioned the material breaks off in a wave like pattern. This implies that as the jet ploughs through the material it carries the ridge from the wake behind it forward until the thickness is such that the adhesive force keeping it on the surface is not great enough and it breaks off under gravity. After the crest of each wave the thickness of the ridge is at its minimum, it then grows in thickness until the next crest and the process repeats itself. As with the case of the 0.2mm film, the falling film is channelled in to the trailing path of the jet by the

Fig 3.13: 1mm film, $2.9cms^{-1}$ moving jet

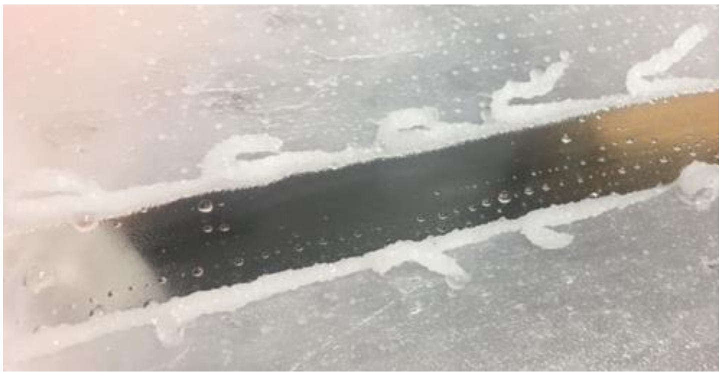


Fig 3.14: WSP detaching from the ridge

ridge and as the flow in the film develops downstream of the impingement point it forms a very narrow stream.

The final dynamic jet experiment was ran on a 1mm film using the -13cms^{-1} moving jet. The resulting clean area is shown in Fig. 3.15. It exhibits a very similar behaviour to that of the case of the 0.2mm film. The diameter of the clean region is approximately that of the jet due to the very short contact time with each part of the surface due to the fast velocity of the plate. The falling film can also be seen to be channelled upwards by the ridge and form a film above the impingement point of the jet. Unlike the 2.9cms^{-1} for the same film thickness, in this case the ridge does not show the same fragmentation and formation of waves. This is due to the fact that the ridge is not as large in volume as it contains less transported WSP. The adhesive force keeping the ridge on the surface is not exceeded by the weight of WSP being carried forward and thus it does not detach.

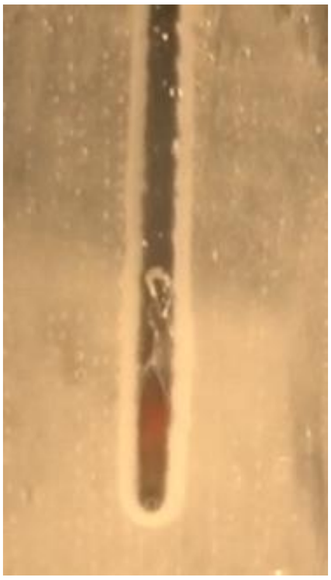


Fig. 3.15: 1mm film, -13cms^{-1} moving jet

The mechanisms observed in the case of the dynamic jet experiments have shown how the relative motion of the jet affects the behaviour of the cleaning. A slower moving plate and thus a slower relative motion of the jet allows more material to be transported and thus forms a larger ridge, as the prolonged contact with each part of the surface allows growth of the clean region closer to the diameter of the film jump for a given flow rate. The direction of the flow also affects the falling film observed, when the jet is moving upwards relative to the surface the falling film conventionally forms underneath the impingement point of the jet. It is however channelled in to a narrow stream by the ridge which isn't observed in the case of the static jet. When the jet is moving downwards relative to the surface, the film forms above the impingement point and is channelled upwards by the motion of the plate. The velocity of the plate and thickness of the film also had a noticeable effect on the pattern formed by the ridge, for a low velocity and high film thickness, the ridge detached at regular intervals and formed waves of WSP in the wake of the jet. This is due to the accumulation of the ridge reaching a point where the adhesive force holding it to the surface is exceeded by the weight of the WSP, causing it to detach due to gravity.

4. Conclusions and Future Work

The short research visit to Cambridge University was a very insightful and useful exercise that has enhanced the progression of the project greatly. The work using the CTS detecting the residual film on the surface after spray cleaning was particularly useful in helping to understand the soil removal mechanisms of the spray in more detail. The extent of the residual film thickness was given whereas this was previously unobtainable without such equipment. This gives an insight in to the volume of material transported by the spray, and knowing the power input for both the jet and the spray the respective cleaning efficiencies for both can be derived. The effectiveness of the CTS has been highlighted and is something that will be considered for use in Leeds. The dynamic jet experiments also provided an interesting perspective on what effect the motion of the jet has on cleaning. Since many industrial cleaning applications involve moving jets it was important to take this in to consideration. Due to time limitations during the two week visit not everything was completed, such as further spray experiments using different flow rates, film thicknesses and standoff distances. This is something that will be carried forward in Leeds and the opportunity for future research visits to Cambridge was highlighted by Prof Wilson if further areas of research require equipment accessible there.