The Effect of Roof Inclination on the Condensation Behaviour of Plastic Films Used as Greenhouse Covering Materials

K. Gbiorczyk and B. von Elsner
Institute of Horticultural and Agricultural Engineering (ITG)
University of Hannover
Herrenhäuser Strasse 2
D-30419 Hannover
Germany
E-mail: elsner@itg.uni-hannover.de

P.J. Sonneveld and G.P.A. Bot
Institute of Agricultural and Environmental Engineering (IMAG)
P.O. Box 43
6700 AA Wageningen
The Netherlands
E-mail: p.j.sonneveld@imag.wag-ur.nl

Keywords: drop-like, contact angle, antifog, dripping behaviour, light reflection

Abstract

Different antifog greenhouse films were investigated concerning their condensation behaviour at different roof inclinations in comparison to a standard copolymer LDPE film. The disadvantage of plastic films used as greenhouse covering in comparison to glass is their hydrophobic behaviour. Drop-like condensation leads to light reflection and to droplets falling onto the plants. Therefore special additives are integrated into the film in order to change the condensation into a water film condensation. The problem is that no standardised testing method for an objective evaluation of the antifog effect of greenhouse films exists. The plastic films for greenhouse covering were characterised by studying the condensed water pattern formation with an IR-camera and measuring relevant physical properties of the film influenced by the condensation, for example, the light reflectance with a reflectometer. The measurements on the greenhouse films were performed under laboratory conditions with a specially designed contact angle measurement device and an inclinable hotbox located in a cold room. It was possible to predict the critical roof inclination of a film concerning the sliding and dripping of droplets with the measurement of single droplets. A certain inclination angle exists also for the antifog films below that the condensate drips down onto the plants. This angle is different for each material. The reflectance measurements showed that there was a critical inclination for a non-wettable material like the standard LDPE-film but not for the tested antifog films.

INTRODUCTION

The disadvantage of plastic films used as greenhouse covering in comparison to glass is their hydrophobic behaviour. Drop-like condensation leads to light reflection and to droplets falling onto the plants depending on roof inclination. Special additives are integrated into the so-called antifog film in order to change the condensation shape into a water film condensation. In general, condensation is characterised to be drop-like or filmwise, but a lot of intermediate conditions exist on commercial antifog films. Briscoe and Galvin (1991) showed that the contact angle between the droplets and the surface is the most important parameter characterising this effect. For small contact angles the liquid spreads over the surface and a water film arises. With the horizontal film a sessile or pendent droplet forms the static contact angle θ_s. The pendent droplet then falls down, due to the expansion, when the force of weight F_W exceeds the vertical component of the adhesional force F_A the surface tension acting upon the base of the droplet:

$$F_W = m \cdot g > F_A = 2 \cdot \pi \cdot r \cdot \gamma_{LA} \cdot \sin\theta_s \qquad [\mathrm{N}] \qquad (1)$$

The droplet on an inclined plastic film forms two different contact angles called dynamic contact angles. The lower angle with the higher value is called the advancing

Proc. XXVI IHC – Protected Cultivation 2002
Ed. A.P. Papadopoulos
Acta Hort. 633, ISHS 2004
Publication supported by Can. Int. Dev. Agency (CIDA)

contact angle and the upper smaller contact angle is the receding angle. The droplet begins to slide when the equilibrium weight is exceeded. The equilibrium weight of a pendent or sessile droplet is related to the dynamic contact angles and the tilt angle by (Furmidge, 1962):

$$m \cdot g = \frac{w \cdot \gamma_{LA} \cdot (\cos\theta_a - \cos\theta_r)}{\sin\alpha} \qquad [\mathrm{N}] \qquad (2)$$

where w is the droplet width [m], θ_a the advancing and θ_r the receding contact angle and α the tilt angle [rad].

Concerning the theoretical dripping behaviour of a droplet, when it begins to slide, no literature could be found. Only little experimental work is done concerning the dripping behaviour of greenhouse films (e.g. Fähnrich et al., 1987; Schultz, 1997). The amount of condensate was dependent on the slope for drop-like but not for film-like condensation. Schultz (1997) and Gbiorczyk (1997) performed experiments on dripping formation of single droplets. The results promised the suitability of a testing method. In contrast, much experimental and theoretical work was done concerning the influence of the condensation form on light transmittance of plastic films. A literature review is given by Sonneveld et al. (2002). There is a strong demand for standardised testing methods for plastic films used as covering material for greenhouses. Therefore the European Standard for greenhouse films DIN EN 13206 (2001): “Covering Thermoplastic Films for Use in Agriculture and Horticulture” was published recently. Nevertheless, there is no instruction for the condensation behaviour included due to a lack of useful and repeatable methods.

The aim of the work was first to investigate the condensate produced in a hotbox concerning the dripping and reflection behaviours in dependence on the film inclination. Secondly in order to simplify the testing procedure, parameters which are tested on artificially applied single droplets, were compared with the condensation behaviour. The dripping behaviour of the condensate was related to the drop shape and critical inclination of single droplets. Further, the connection between drop shape and the reflection of light was investigated.

MATERIAL

The methods were investigated with greenhouse films (200 µm three-layer copolymer of LDPE and EVA) produced by HYPLAST NV (Belgium). A standard greenhouse film (*standard*) was compared with experimental antifog films containing commercial (*antifog 1* and *antifog 3*) or experimental additives (*antifog 2*) produced by CIBA Speciality (Italy) and the commercial film HYTILUX (*antifog 4*).

METHODS

Determination of the Critical Inclination for Pendent Droplets

The contact angle measurement device using the tilted-plate and goniometry method described by Schultz (1997) was used in an improved design for measuring the contact angle and the sliding of single droplets. For the experimental determination of the critical inclination of pendent droplets, the droplet is placed as a sessile droplet, in sizes beginning with 10 µl in incremental steps of 10 µl until the maximum volume, on the sample. Pendent droplets are obtained by turning the carrier carefully upside down. The carrier is then slowly tilted by increments of 2° until the critical inclination of sliding. The measurement was repeated three times.

Measurement of the Contact Angle on Sessile Droplets

The aim of the investigation of sessile droplets of a certain size was to simplify the testing method instead of pendent droplets of a range of sizes (*sessile-method*). This method would be easier to apply and would be time-saving. However, the method neglects the fact that, in contrast to the advancing or receding contact angle, droplet width depends on size of the droplet and gravitation.

A sessile droplet with a certain volume (80 µl) of distilled water (γ_{lv} = 73 mN m^{-1}) is placed on the film using a variable-volume pipette. The static contact angle is measured at a picture of the lateral droplet profile taken at the horizontal film, the dynamic contact angles at the moment when the droplet begins to slide. The droplet width is calculated with the length-to-width aspect ratio of the contact line (Extrand and Kumagai, 1995). The measurement is repeated at 10 different places on the sample. Equation 2 was then used for the calculation of the critical inclination for sliding. The calculation was done until the maximum droplet mass that remains hanging on the horizontal film, calculated with equation 1.

Set-up for Methods Applied on Condensate

At the ITG Schultz (1997) built a hotbox specially designed for monitoring the condensation behaviour of greenhouse films under controlled conditions. Mainly due to the restriction of a fixed roof angle, a new structure was designed as depicted in Figure 2. The angle of the greenhouse roof segment is now continuously adjustable from 0 to 40°. The hotbox (air temperature 25°C) is placed in a conditioned cold room (2°C). The greenhouse film sample is fixed into an aluminium frame. A hot steam humidifier increases air humidity inside the hotbox. The run off and the dripped condensate are collected separately in gutters. The reflection of direct (normal incident) and diffuse light (644 nm) is measured with a reflectometer (Sonneveld and Gbiorczyk, 2000; Gbiorczyk, 2001), which can be fixed on the film frame. A detailed description can be found in Sonneveld et al. (2002). The surface that is evaluated by reflection, is about 50 cm².

The Critical Inclination for Condensation

The critical condition for condensate is defined here as the angle where the condensation behaviour changes. The critical inclination is the steepest inclination where the condensate does not slide and consequently remains fixed or drips down. To estimate the critical inclination of condensate the following method is used. The method analyses the sliding behaviour of single droplets and is therefore called *sliding-method*. The lowest occurring inclination of sliding is taken from the calculated and experimental mean plot of critical inclination against droplet volume. The critical angle for condensate is consequently one degree below this inclination. For each film in the hotbox, the dripped and run-off condensate was collected at 0°, 30° and 40° inclined film in addition to at least two other angles around the estimated critical inclination.

RESULTS AND DISCUSSION

Contact Angle and Droplet Width of Sessile Droplets

The static contact angle of the *standard* film is at 84 ± 5° the highest of the tested materials. This value agrees well with the values given in literature for a polyethylene greenhouse film (e.g. Jaffrin and Guion, 1994: 85°). Three antifog films have a lower static contact angle of about 57° (*antifog 1* 58 ± 3°, *antifog 2* 56 ± 10° and *antifog 3* 58 ± 4°) and the lowest value is found at 39 ± 4° on *antifog 4*. The high standard deviation of *antifog 2* can be attributed to the heterogeneous distribution or migration of the additives. It is observed that the droplet width increased with decreasing contact angle thus as expected the droplet is more spread out on wettable materials (*standard* 0.64 ± 0.020 cm, *antifog 1, 2* and *3* about 0.82 ± 0.053 cm and *antifog 4* 0.96 ± 0.035 cm).

The observations are very similar for the dynamic values. The highest angles were measured on the *standard* film (receding 57° ± 8, advancing 84° ± 3), followed by the three similar antifog films (*antifog 1*: receding 14° ± 3, advancing 61° ± 3; *antifog 2*: receding 25° ± 14, advancing 65° ± 8; *antifog 3*: receding 19° ± 4, advancing 66° ± 3). The film displaying the lowest values is *antifog 4* (receding 17° ± 3, advancing 51° ± 7). So the ranking of the advancing contact angle is the same as for the static measurement.

Again the measurement of the film *antifog 2* is the least reproducible. It can be summarised that, based on the contact angles, the commercial film *antifog 4* with the lowest static and advancing angle seems to be the most wettable of the tested materials. It is followed by films *antifog 1*, *antifog 2* and *antifog 3* with similar wettability and the *standard* film being the least wettable.

Critical Inclination of Sliding

The experimental and calculated critical inclination of a single droplet plotted against the droplet volume is given in Figure 1. In general the repeatability of the measurement is very good whereas the highest deviation is observed with the commercial film *antifog 4*. Significant coincidence between experimental and all calculation methods is obtained for the films *standard*, *antifog 1* and *antifog 3*. Also for film *antifog 4* the results of the different calculation methods do not differ, whereas the experimental deviation is high. For film *antifog 2* the calculated curve is slightly shifted.

Estimation of the Critical Condition for Condensate

The *sliding method* results in defined critical angles (Table 1). The critical angle is calculated at 7° for the *standard* film and between 8 and 12° for the antifog films. From the experiment for single droplets, it follows that the highest mean value of the critical inclination at which a droplet of any size begins to slide is 12° for antifog film 3. The droplets begin to slide on *antifog 1* at 10°, at 9° on the *standard* film, at 7° on *antifog 2* and almost immediately at 1° on the commercial film *antifog 4*. Increased dripped water below and run-off water above these angles is expected. The experimental results of this method do not differ significantly from the calculation except for the film *antifog 4*, which was accompanied by the lowest repeatability.

Collected Amounts of Condensate

The collected amounts of water are visualised as a quantity normalised to the evaporated water in Figure 3. The drop-like condensation on the *standard* film was very static below 15°. No sliding of droplets was observed and hardly any dripping occurred. This observation differs from the results of Fähnrich et al. (1987) and from the situation in commercial greenhouses due to the lack of film movement which occurs in laboratory conditions. In practice flexible covering material is stirred by the wind and consequently the droplets fall down easier. However, as in the experiment of these authors, above this critical angle the run-off water increases with inclination and the maximum dripped water quantity was collected at 15 and 30°. The condensate on the antifog films which have water films or mixed condensation shapes is much more in motion; hence the quantity of collected water is much higher from the antifog films than from the *standard* film. This was also observed by Fähnrich et al. (1987) and Geoola et al. (1994). Between angles of 15 and 40° the antifog films showed good condensation behaviour without dripping. However, below these critical inclinations the dripping is immense. In the example where the film is inclined more than 15°, there is no difference between the tested antifog films. Nevertheless, for the critical greenhouse surfaces at lower angles the films *antifog 3* and *antifog 4,* which exhibit similar dripping behaviour, are the most suitable. The other films are evaluated as unfavourable due to the immense dripped water quantity (*antifog 1*) and lack of run-off water behaviour (*standard* and *antifog 2*).

Comparison between Testing Methods to Evaluate the Dripping Behaviour

In general the results of the *sliding-method* coincide with the condensate experiment. This is not the case for the film *antifog 4,* where the experimental critical inclination for the condensate between 7 and 14° does not coincide with the 2° inclination, estimated by the experimental sliding results. Nevertheless, the calculated value of 12° agrees well with the hotbox result. Therefore this difference can be attributed to the high deviation of the sliding behaviour of a single droplet on this film. A certain experimental error is caused by the time-intensive condensate method, which restricts tests to increments of 4-17°. With this testing method, only the change of the condensation behaviour can be determined. The condensate drips or runs off depending on the geometry of the condensate. Therefore the contact angle must be included in the evaluation. The measured contact angles of the materials with film condensation exceed the expected boundary value of 40°. According to the results it can be concluded that an advancing contact angle of a sessile droplet higher than 70° results in droplets at any inclination. Under laboratory conditions without movement of the film the critical inclination means static condensation below and sliding and dripping due to coagulation beyond this tilt angle. For contact angles lower than 70° condensation is more or less film-like with high dripped amounts below the critical angle and run off condensate at higher inclinations.

Reflection of Light

With the horizontal *standard* film the reflection of diffuse light is increased due to the static drop-like condensation by 6% when compared with the dry film (Fig. 4). This value agrees well with published calculations (Sonneveld et al., 2002). At higher inclination angles, 15 and 30°, the condensation begins to run-off after a certain time leading to a somewhat lower reflection increase (4%). These values remain significantly below those calculated by Pollet and Pieters (2000), which are 11-13% for a vertical film and 19% for a 25° inclined material. These values agree with measured values of Fähnrich et al. (1987) (8%). In general, light reflection is decreased from 0.5-3% the condensation on the antifog films which agrees with the literature. Only the mixed condensation pattern on the film *antifog 2* leads to a slight reflection increase. The peak can be explained by expanding drop-like condensation that changed later into a cordy film with single droplets. With the antifog films the effect of inclination has significant influence only for *antifog 3* where an angle of 30° leads to 2% more light in comparison to 10°. As well, this film is the best-tested antifog film concerning its diffuse light reflection capability, followed by *antifog 1*, *antifog 4* and *antifog 2*.

For drop-like condensation on the horizontal *standard* film with 17-23% inclination, the reflection of direct light is much higher than that of diffuse light (no incline). This agrees very well with the published values of literature (e.g. Pollet and Pieters, 2000). The results of the wet antifog films (0 and -3.6%) are similar to those obtained with diffuse light and are independent on the roof inclination as described in the literature.

Comparison between Single Droplet and Condensate Testing Methods

After analysing the ranking results of the different testing methods only one direct connection can be seen between the measurement of a single droplet and the condensate: the contact angles of the sessile droplets describe the behaviour of the condensate in regards to the ratios of run-off and dripped water. The ranking for the contact angles and dripping behaviour is the same for both methods: the commercial film *antifog 4* is the most wettable, followed by the films *antifog 1*, *antifog 3*, *antifog 2* and the non-wettable material *standard*. The ranking for reflection is different: *antifog 1* has the highest light (644 nm) reflection decrease, followed depending on type of light by *antifog 3* and *antifog 4*, then at the penultimate position the worst antifog film *antifog 2* and with the *standard* film having the least favourable behaviour.

CONCLUSIONS

The first objective was to develop a testing method to measure the condensate. The dripping behaviour in conjunction with the roof inclination was tested. The tests resulted in a new set-up where the run-off and dripped water is collected and weighed. The dripping behaviour strongly depends on roof inclination for all materials. Consequently the testing method must include different angles. Particularly for antifog films the tilt angle must not be lower than the critical inclination because this leads to immense dripping. Also the light reflection was tested depending on the roof inclination.

The result is a new testing method with a hotbox and a reflectometer. The optical properties in the PAR depend on the roof inclination only for drop-like condensation. Consequently for antifog films it is satisfactory to perform one measurement at any inclination.

The second objective was to develop a testing method, which measures the behaviour of single droplets. Firstly the connection between drop shape and critical inclination and the dripping behaviour of the condensate was tested. The result is a new testing method with single droplets because it is possible to describe the dripping behaviour of the condensate with the measurement of the shape of single sessile droplets. The testing parameters are the static and dynamic contact angles and the droplet width. In comparison to generate condensation this method has lower set-up and labour costs and it is therefore an approach to the standardisation of testing methods. In addition the connection between drop shape and reflection on the condensate was investigated. There is no indication that the contact angle of artificially applied single droplets can describe the visible light properties of wet plastic films. Therefore the testing on real condensate still remains important.

The presented results of the dripping behaviour still must be compared with condensate in commercial greenhouses.

ACKNOWLEDGEMENT

The present work is carried out under the “Standard, Measuring and Testing” research programme funded by the E.U.: “New testing methods for plastic films used as greenhouse covering materials”. Participants are the Dept. of Agr. Eng. (Agr. Univ. of Athens, G), Division GEMO (CEMAGREF Montpellier, F), CIBA Speciality S.p.A. (I), Inst. of Agr. and Environm. Eng. (IMAG, NL), HYPLAST NV (B) and the Inst. of Hort. and Agr. Eng. (Univ. of Hannover, D).

Literature Cited

Briscoe, B.J. and Galvin, K.P. 1991. The effect of surface fog on the transmittance of light. Solar Energy 46:191-197.

DIN EN 13206. 2001. Covering Thermoplastic Films for Use in Agriculture and Horticulture.

Extrand, C.W. and Kumagai, Y. 1995. Liquid drops on an inclined plane: The relation between contact angles, drop shape and retentive force. J. Colloid and Interface Sci. 170:515-521.

Fähnrich, I., Meyer, J. and von Zabeltitz, C. 1987. Einfluss der Kondensation auf Licht- und Wärmedurchgang von Gewächshausbedachungsmaterialien. p.99-109. In: Zukunftsorientierte Pflanzenproduktion mit Kunststoffen, KTBL-Arbeitspapier 125, KTBL, Darmstadt.

Furmidge, C.G.L. 1962. Studies at phase interfaces. I. The sliding of liquid drops on solid surfaces and a theory for spray retention. J. Colloid Sci. 17:309-321.

Gbiorczyk, K. 1997. Untersuchung der Tropfengeometrie zur Bewertung des Kondensationsverhaltens von Gewächshausfolien. Diplom Thesis, Inst. Hort. Agri. Eng., Univ. Hannover, Germany, unpublished.

Gbiorczyk, K. 2001. Prüfverfahren für Gewächshausfolien – Messung der Reflexion des Lichtes an kondensiertem Wasserdampf. p.47-53. In: KTBL-Arbeitspapier 277, KTBL, Darmstadt.

Geoola, F., Peiper, U.M. and Geoola, F. 1994. Outdoor Testing of the Condensation Characteristics of Plastic Film Covering Materials Using a Model Greenhouse. J. Agr. Eng. Res. 57:167-172.

Jaffrin, A. und Guion, J. 1994. The molecular origin of surface phenomena as affects the optical transmission of polymer films. Plasticulture 102:41-57.

Pollet, I.V. and Pieters, J.G. 2000. Condensation and radiation transmittance of greenhouse cladding materials, part 3: Results for glass plates and plastic films. J. Agr. Eng. Res. 77:419-428.

Schultz, W. 1997. Verfahren zur Untersuchung und Bewertung des Kondensationsverhaltens von Gewächshausfolien. Schriftenreihe Gartenbautechnische Informationen, Heft 41. Ph.D. Thesis, Inst. Hort. Agri. Eng., Univ. Hannover, Germany.

Sonneveld, P.J. and Gbiorczyk, K. 2000. Reflection measurements of greenhouse covering materials during condensation. Abstract. Proc. 15th Intl. Congress for Plastics in Agriculture (CIPA), Hershey, Pennsylvania, USA, 23-27 September. p.224.

Sonneveld, P.J., Gbiorczyk, K., von Elsner, B. and Bot, G. 2002. Reflection measurements of greenhouse covering materials during condensation. Proc. Ag. Eng. June 2002, Budapest, will be published in Biosystems Engineering.

Tables

Table 1. Critical inclination [°] determined by different methods.

Material	Single droplet		Condensate
	calculated	experimental	experimental
standard	7	9	10-14
antifog 1	10	10	8-14
antifog 2	8	7	7-24
antifog 3	12	12	10-14
antifog 4	12	2	7-14

Figures

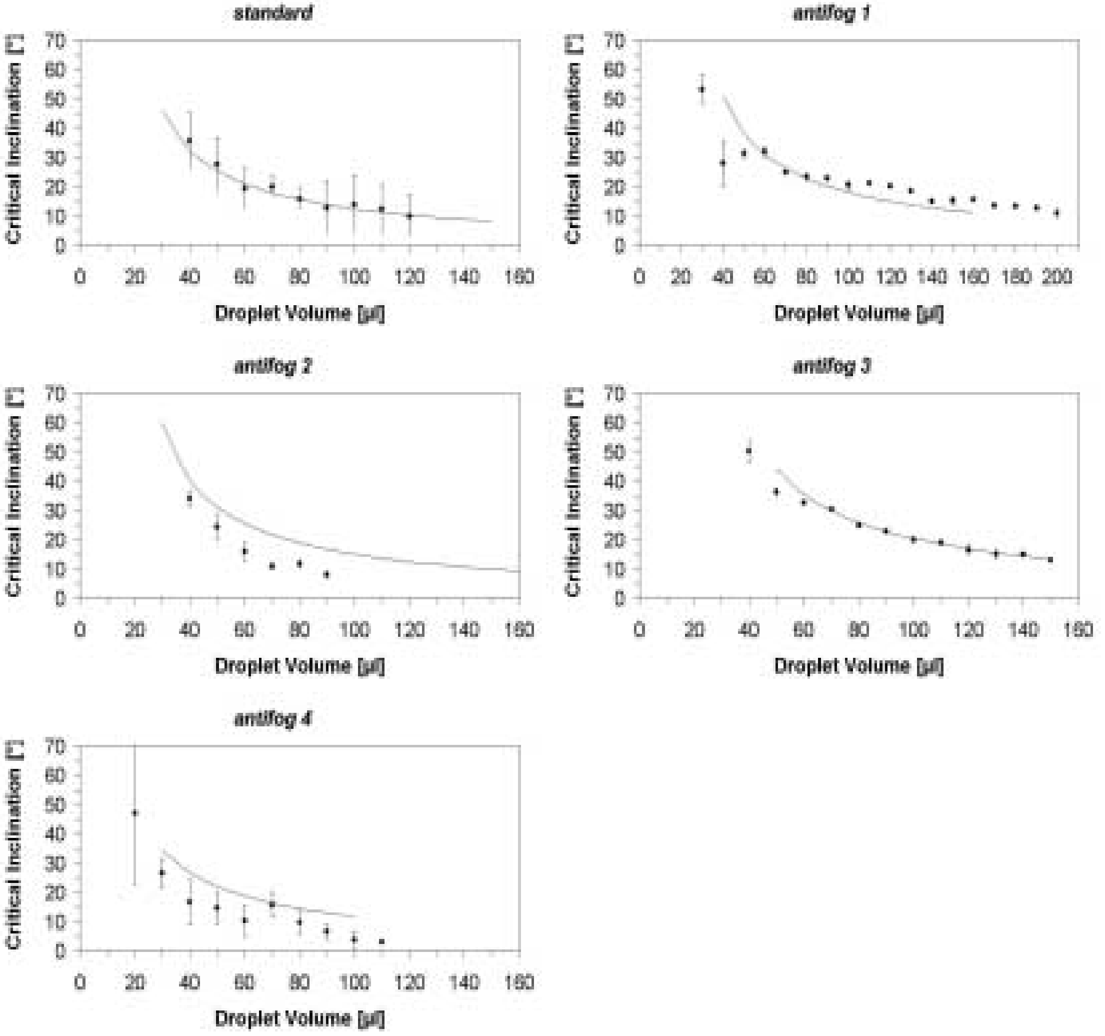

Fig. 1. Critical inclination of sliding of single droplets for the applied materials (line: calculated with shape of sessile droplets, dots: measured on pendent droplets).

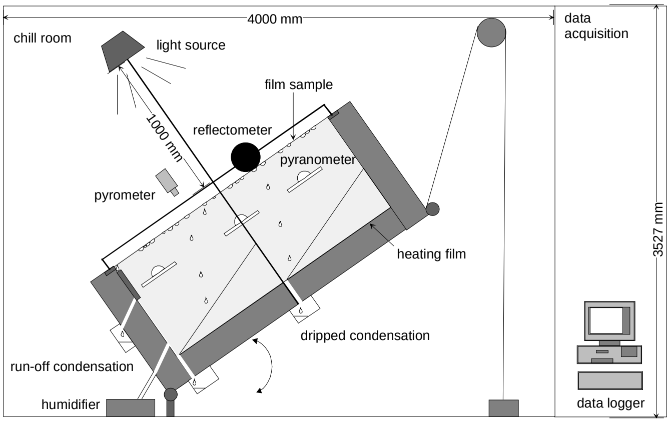

Fig. 2. Cold chamber with hotbox.

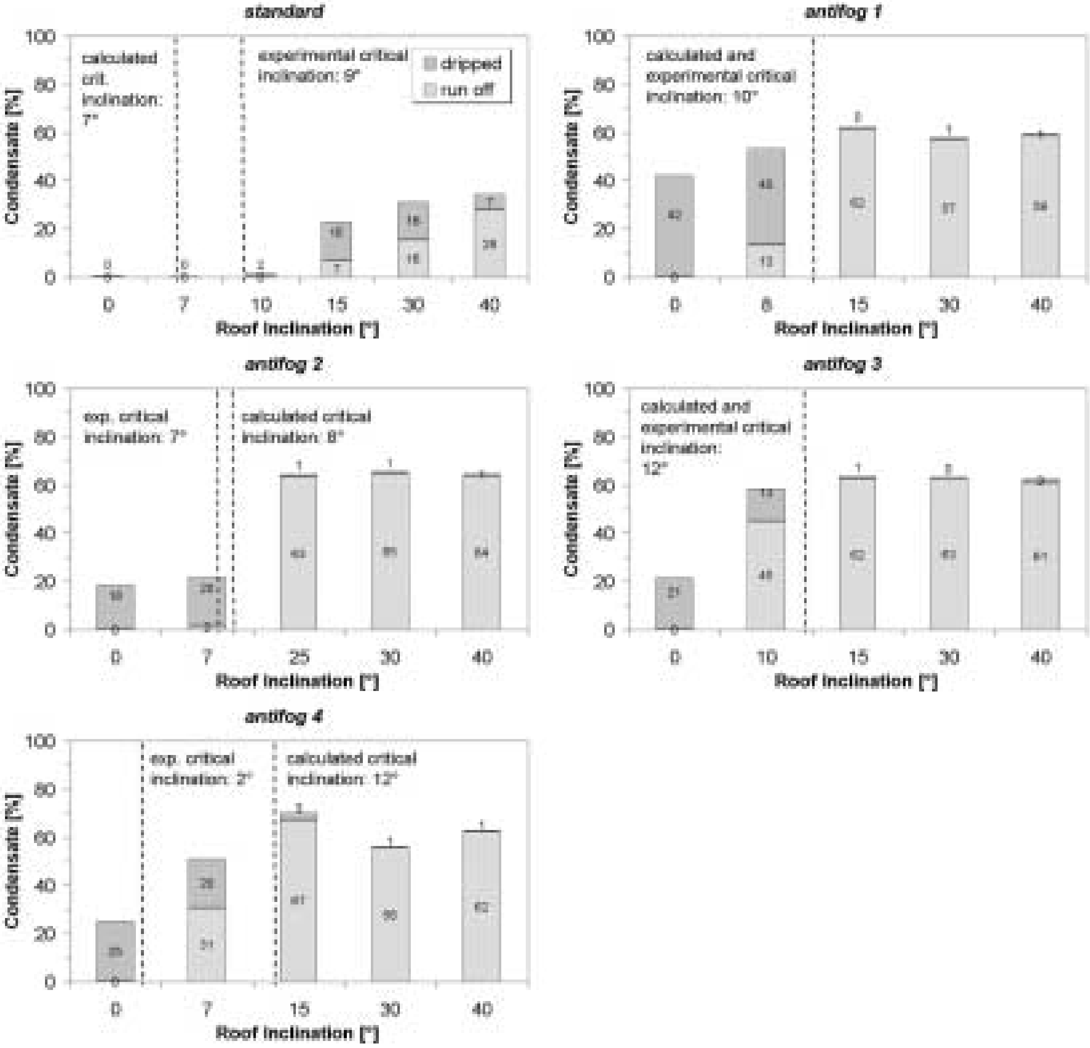

Fig. 3. Run off and dripped condensate for the various applied materials at different film inclinations.

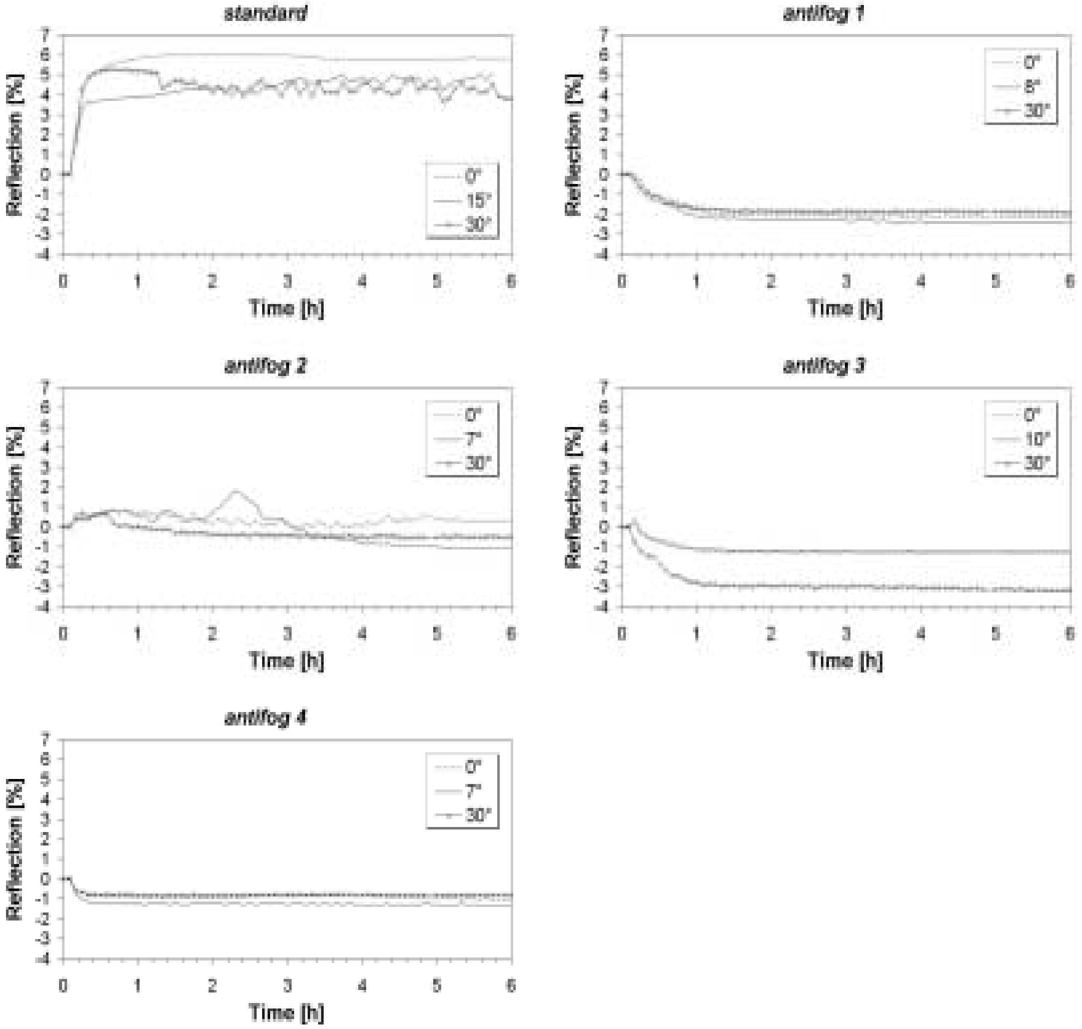

Fig. 4. Reflection due to condensation for the various applied materials at different film inclinations (diffuse light).