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FREE-SURFACE PHENOMENA

UNDER

LOW- AND ZERO-GRAVITY CONDITIONS

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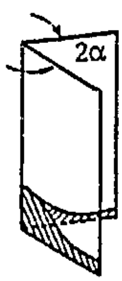
ABSTRACT

An apparatus for measuring contact angle has been constructed to exploit the internal-corner criterion proposed by Concus and Finn (Proc. Nat. Acad. Sci. 63, 292, 1969). If 2α is the internal angle between two intersecting vertical planes and γ is the contact angle, a meniscus at the corner rises to a finite height if $\alpha + \gamma > \pi/2$, and to an infinite height if $\alpha + \gamma < \pi/2$. The apparatus operates by decreasing the angle α from $\pi/2$ until the meniscus height changes abruptly. A number of liquids have been tested on glass and plexiglas.

Overview. The three principal experimental elements of the capillary or free-surface problem are geometry, materials, and instrumentation. In this research program, geometry is primarily the responsibility of Paul Concus at UCB and Robert Finn at Stanford. Materials are primarily the responsibility of Donald Coles at Caltech, aided by a consultant (yet to be named) on questions of physical and surface chemistry. Instrumentation is primarily the responsibility of Lambertus Hesselink at Stanford.

The shape of a capillary surface depends on container geometry, liquid density, apparent gravity, surface tension, and contact angle. The contact angle, which enters through the boundary condition for the governing equation, is usually assumed to be a property only of the materials involved. The contact angle is known to be sensitive to many factors, including temperature, surface roughness, composition of the third phase, contamination of the solid surface or the liquid volume, and direction of approach; i.e., whether the contact line is advancing, stationary, or receding. Hence it is not surprising that there is substantial lack of agreement among various measured values for particular combinations of liquid and solid.

The corner method for measuring contact angle. Concus and Finn (1969) have described a property of capillary surfaces which in principle provides a method for measurement of contact angle. Consider a capillary surface in a corner between two plane walls, as shown in the sketch. As



the internal angle 2α decreases from 180°, the liquid rises continuously in the corner, until α reaches the critical angle $\pi/2 - \gamma$ (γ is the contact angle). For all smaller values of α, the liquid in the corner rises to infinity. There is thus an easily detectable discontinuity in the shape of the meniscus when $\alpha + \gamma = \pi/2$.

During the contract period covered by this report, an apparatus was constructed to measure contact angle by exploiting this internal contact-angle criterion. The apparatus is shown in Fig. 1. Two glass microscope slides (25 mm x 75 mm x 1 mm thick) are kept in contact by an arrangement of springs. The angle between the two slides can be smoothly changed from 180° to about 20°; i.e., contact angles from 0° to about 80° can be measured. The slides are placed with their lower ends in a petri dish (60 mm diameter, 15 mm deep) containing about ten cc of liquid. The apparatus is lighted by a diffuse fluorescent light source from the rear and by a concentrated incandescent light source from the front. The view of the meniscus is magnified about thirty times by a binocular microscope.

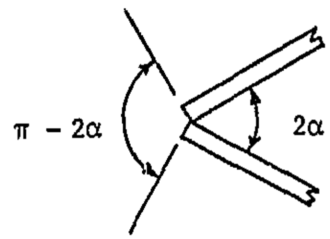
All experiments were conducted in a fume hood to avoid contact with harmful vapors. Various methods were tried for cleaning the glass slides. These included soaking in concentrated nitric acid, boiling in distilled water, washing with Dichrol (a potassium dichromate-sulfuric acid solution), and washing with Freon 113 (1,1,2-trichloro-1,2,2-trifluoroethane). The contact angle of water was measured on slides cleaned by the various methods, and the methods were rated by the reproducibility of the measurements. The method finally chosen was a three-minute ultrasonic bath in Freon 113. Similar trials were made for plexiglas, including washing with detergent solution 409, with a commercial cleaner (MS-260), and with various soaps (Labtone, Ivory soap, Palmolive liquid). The method chosen was washing in MS-260 (65% water, 5% 2-butoxyethanol, 30% various alcohols and additives).

The slides were clamped to the apparatus, adjusted for smooth motion, and inserted in the liquid with $2\alpha = 180°$. Then the angle between the two slides was slowly decreased from 180° until a discontinuity--the disappearance of the sharp tip for the contact-line profile at the advancing contact angle--was observed. The angle was then slowly increased until the sharp tip reappeared at the receding contact angle.

About 100 liquids were tested. Hysteresis for advancing and receding contact lines was highly variable, ranging from 1° (1-bromobutane, several esters) to 25° (1-octanol), with most values in the range from 3° to 8°. Most liquids had mean contact angles on glass in the range from 5° to 15°. The contact angle for water on glass was about 35°. Some correlation was found between contact angle and chemical structure. Among the straight-chain alcohols (ethanol, 1-propanol, 1-butanol, 1-pentanol, 1-hexanol, 1-octanol) and the straight-chain aldehydes (butanal, pentanal, heptanal), the contact angle tended to increase with the number of carbon atoms in the chain, both on glass and on plexiglas. The contact angles for the straight-chain ketones (2-propanone, 2-butanone, 3-pentanone, 2-octanone) were all about 5.7° to 8.2° ±20%. The glycols as a family had larger contact angles (10° to 27° on glass, 37° to 67° on plexiglas).

As with most new methods, the method had some problems. Liquids with high indices of refraction and high boiling points (100°C and above) gave fairly consistent measurements. However, there was a real discontinuity in meniscus shape only for water, dibromomethane, benzyl formate, and butyl benzoate. The meniscus was hard to see for many liquids because the indices of refraction were often close to those of glass or plexiglas. Some of the liquids, especially the glycols, were known to be hygroscopic. Their contact angles tended to decrease with time as the liquid absorbed more and more water. Some liquids were very viscous, and would not drain off the slides; examples are glycerin and triethylene glycol on glass. In fact, none of the liquids drained completely. The contact angle of a liquid could decrease significantly between the first and second readings because of wetting. The contact line was often very ragged, making it difficult to tell what the profile really looked like. It was particularly difficult to estimate the contact angle for liquids with low boiling points, such as acetone or ethanol. As soon as the surface developed a sharp tip, it evaporated away. Many of the more volatile liquids would evaporate, condense on the slides a few millimeters above the contact line, and drip back down, making it difficult to observe the meniscus.

In view of these problems, the corner-angle method turns out to be a marginally usable method for measuring contact angle. A measurement takes about ten minutes and requires about 10 cc of liquid. The solid material need not be transparent. The method works best with liquids having a high index of refraction and a high boiling point. If necessary, the apparatus can be put in a glove box where temperature, vapor pressure, humidity, and contamination can be controlled. An apparently irreducible disadvantage of the geometry, illustrated in the second sketch, is that the criterion



$\alpha + \gamma < \pi/2$ will always be exceeded for the rear corner before it is exceeded for the front corner, unless $\gamma > 45°$. Ideally, the two corners should be isolated by a seal, but no sealing method has been found. Finally, it is not obvious that the effects of contact-angle hysteresis are properly accounted for in the underlying theory. The technique is probably most useful for quick comparative tests such as determining the effect of impurities or the effect of a particular cleaning procedure.

<u>The refraction method for measuring contact angle</u>. Selected liquids or liquid pairs (see below) will eventually be subjected to rigorous study of contact-line behavior, using a technique which should allow accurate measurement of contact angle. The method is to partially submerge a glass plate at a known angle and to observe the refraction of parallel light

(entering from above) by the interface. The contact angle is the angle of the glass plate for which the refracted light has uniform intensity (experiments so far indicate that this condition may never be exactly achieved in practice). To increase the spatial resolution near the contact line and to gain access to dynamic phenomena, the parallel light in the apparatus under development is a scanning laser beam, the detector is a 1024-element photodiode array, and data acquisition is controlled by a small computer.

Two-liquid systems. Preliminary work at Stanford on instrumentation of the proposed experiment suggests that there are advantages in working with an internal meniscus between two immiscible liquids. Considerable progress has been made at Caltech in identifying suitable liquid pairs which involve no serious toxic hazards and are otherwise well behaved; i.e., free of anomalies caused by coating of walls or by formation of nearly permanent emulsions. Good results are obtained when one liquid is hydrophilic (examples are formamide and several glycols) and the other liquid is hydrophobic (examples are brominated hydrocarbons, several esters, and a few alcohols and ketones). Of several dozen such pairs so far found, some of the most suitable seem to be

methyl laurate/ethylene glycol
1-bromodecane/triethylene glycol
methyl laurate/1,2-propanediol
2-octanone/formamide
tributyrin/formamide

This work on selection is continuing. An acceptable preliminary measurement of internal contact angle for such pairs is being made by direct observation, after minimizing refraction at the walls of a glass test tube containing the liquids. The refractive index of borosilicate glass can be closely matched, for example, by a suitable mixture of methanol and methyl benzoate. Simultaneous measurement of the overall vertical dimension of the meniscus, and use of the numerical analysis published by Concus (1968), can also provide a rough estimate of surface tension at the interface between the two liquids.

References

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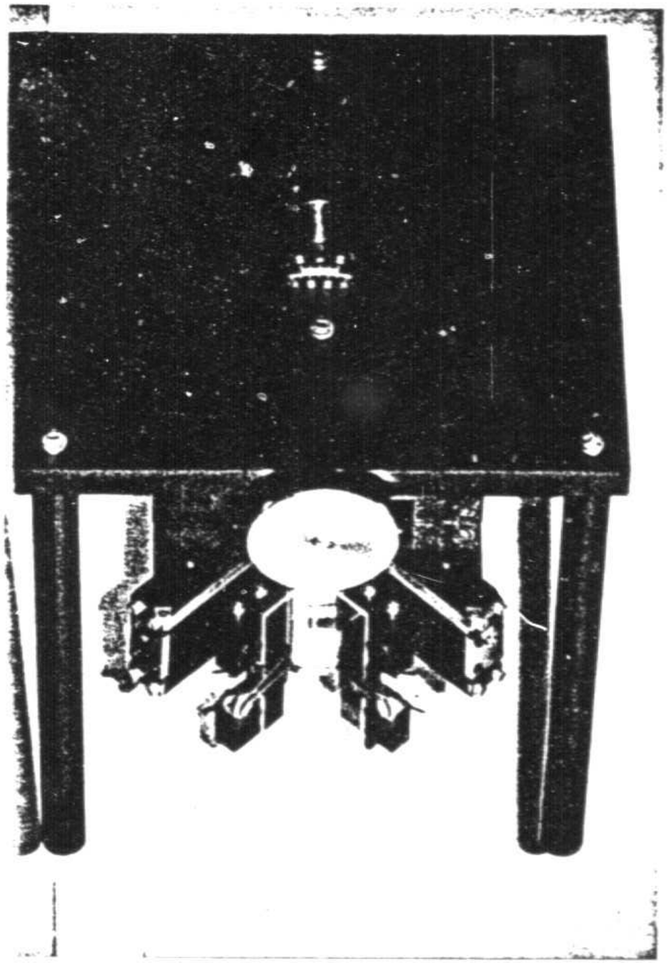
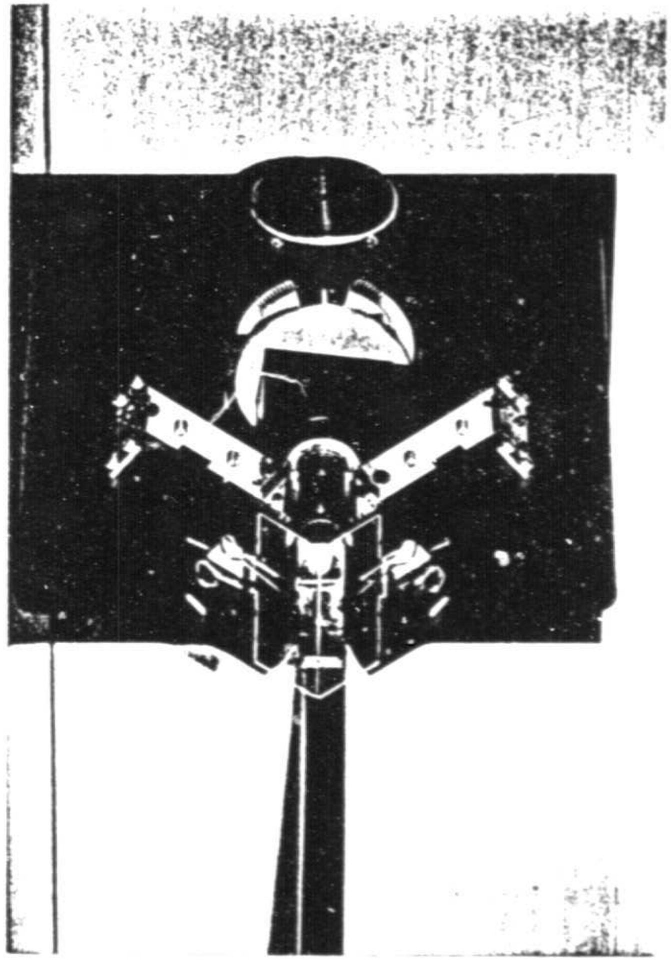
Concus, P. 1968 Static menisci in a vertical right circular cylinder. J. Fluid Mech. 34, 481-495.



Front/top view



Front/bottom view

Fig. 1. Apparatus used for measurement of contact angle.

CONTACT ANGLES OF VARIOUS LIQUIDS ON GLASS

Chem. Service No.	Liquid	#	$\gamma_{up} \pm \sigma$	$\gamma_{down} \pm \sigma$	$\gamma_{est.}$	T (°C)
-	Water	5	38±1°	15±0.8°	30°	24°
	HALOGEN-SUBSTITUTED HYDROCARBONS					
633	Dibromomethane	4	12.4±1°	7±0°	12°	26°
		2	13.5±0.7°	4.5±0.7°		
		3	13.8±0.3°	5.7±0.6°		
618	2-bromopropane	7	9.8±2°	9.1±1°	10°	26°
3110	2-chloropropane	7	16.1±1°	13.6±1°	10°	26°
601	1-bromobutane	8	10.9±1°	9.6±1°	5°	25°
621	Chlorobutane	5	7.9±0.4°	3.5±0.7°	5°	24°
3040	Isobutyl chloride	6	8±0.7°	2.3±0.5°	2°	23°
2385	1-bromooctane	5	8±2°	4±1°	5°	26°
		5	7.9±1°	3.6±1°		
666	Bromobenzene	4	9.8±1°	5.5±0.6°	20°	25°
		5	17.2±2°	4.4±1°		
2450	2-bromotoluene	5	13.8±0.8°	2.8±1°	10°	26°
		5	13.6±2°	1.6±1°		
672	2-chlorotoluene	5	8.8±2°	1.3±0.3°	10°	25°
		5	11.6±0.9°	2±1°		
	ALCOHOLS					
151	Ethanol	5	7.2±0.4°	4.4±0.4°	-	24°
161	1-propanol	5	9.1±0.9°	3.3±1°	5°	25°
		5	9.3±0.4°	2.8±0.8°		
142	1-butanol	5	13.1±2°	2.6±0.9°	5°	25°
		5	12±1°	2.2±0.8°		
139	1-pentanol	5	12.4±1°	6.9±0.4°	12°	25°
		5	12.5±1°	2.4±0.5°		
155	1-hexanol	6	10±0°	8.4±2°	5°	26°
166	1-octanol	5	28.2±3°	4.1±0.7°	30°	26°
		4	30.8±1°	3.8±1°		
213	α-hydroxytoluene	5	13.5±2°	6.1±0.9°	5°	-
218	2-phenylethanol	6	13±2°	6.5±1°	15°	25°
		6	13.3±1°	7.3±1°		
168	2-propanol	5	9.7±0.4°	2.4±0.5°	5°	25°
		5	9.8±0.3°	4±0.8°		

CONTACT ANGLES ON GLASS (cont.)

	ALCOHOLS (cont.)					
6788	3-pentanol	5	7.8±0.4°	4.2±0.8°	3°	25°
		5	9.7±1°	3.3±0.6°		
143	2-methyl-1-propanol	5	17.4±0.9°	7.1±0.7°	6°	25°
		5	10.9±0.7°	3.8±2°		
158	2-methyl-3-butyn-2-ol	5	8.9±1°	3.9±1°	10°	24°
		4	9.5±0.6°	3.1±0.6°		
153	2-ethyl-1-hexanol	5	6.1±0.7°	3.5±0.5°	5°	24°
3310	Cyclohexylmethanol	5	16.6±1°	6.2±1°	15°	24°
		6	12.4±0.8°	4.5±1°		
188	2-mercaptoethanol	5	22.6±2°	---	-	-
		5	19.1±2°	5±0°		
	GLYCOLS*					
7990	2,2'-dihydroxydiethyl sulfide	-	27°	---	25°	24°
205	1,2-propanediol	-	10°	---	8°	24°
195	Glycerin	-	23°	2°	25°	23°
210	Triethylene glycol	-	20°	---	8°	25°
5880	2-methyl-2,4-pentanediol	10	16.9±1°	13.1±1°	18°	26°
	ESTERS					
396	Carbonic acid dimethyl ester	6	7.7±1°	6.8±0.8°	7°	25°
395	Carbonic acid diethyl ester	5	8.5±0.7°	6.4±0.4°	10°	23°
		4	11±1°	6.3±0.3°		
4135B	Malonic acid dimethyl ester	5	23.5±1°	6.8±2°	25°	26°
4646E	Malonic acid diethyl ester	6	5.3±0.5°	2.3±0.5°	5°	24°
421	Acetic acid methyl ester	7	6.9±1°	2.9±0.7°	-	24°
412	Acetic acid ethyl ester	5	7.4±0.5°	3±0.8°	4°	25°
443	Acetic acid 2-ethoxyethyl ester	2	10.5±0.7°	6.8±0.4°	5°	24°
		6	9.3±2°	6.2±0.9°		
438	Acetic acid isopropyl ester	5	12.4±2°	7.2±1°	5°	26°
		5	14.4±2°	7.8±1°		
436	Acetic acid isopropenyl ester	5	9.9±2°	9.2±2°	5°	26°
		4	13±1°	8.5±2°		
416	Acetic acid 2-ethylhexyl ester	5	6±2°	1.3±0.4°	5°	25°
		5	3.1±0.9°	2.3±1°		
418	Propanoic acid ethyl ester	5	10.3±1°	9.4±0.5°	10°	26°
1004	Propenoic acid butyl ester	5	10.6±0.9°	4.9±0.4°	5°	26°
		4	11±0.8°	4.8±0.5°		
413	Butanoic acid ethyl ester	6	4.2±0.8°	0.7±0.7°	5°	26°
		5	1.8±0.3°	1±0.1°		

CONTACT ANGLES ON GLASS (cont.)

	ESTERS (cont.)					
1965B	Butanoic acid 3-methyl-	6	13.7±0.8°	5.3±0.4°	5°	26°
	butyl ester	6	7.8±3°	3.7±1°		
PZ5	Tetradecanoic acid	3	9±0°	8±0°	-	-
	isopropyl ester					
919	Phosphoric acid triethyl	5	9.6±0.4°	5.1±0.5°	8°	25°
	ester	4	11.5±1°	4.4±0.5°		
916	Phosphoric acid tributyl	5	15.9±4°	2.4±0.5°	7°	25°
	ester	5	13.2±0.6°	2.7±0.8°		
463	Malonic acid monoethyl	5	11.2±0.8°	6.8±0.4°	15°	25°
	ester mononitrile	5	12.2±0.8°	7±0°		
5740A	Chloroacetic acid methyl	5	5.3±1°	2.6±1°	5°	26°
	ester					
2145B	Formic acid benzyl ester	5	8.3±0.4°	3±1°	10°	24°
		4	9±0.7°	3.5±2°		
1980	2-hydroxybenzoic acid	5	23.4±1°	2.1±0.9°	20°	-
	3-methylbutyl ester					
486	Succinic acid diethyl	5	9.3±0.3°	---	10°	-
	ester	4	9.3±0.5°	6±0.5°		
465	3-oxobutanoic acid ethyl	10	17.1±2°	11.9±2°	15°	26°
	ester					
482	Maleic acid diethyl ester	6	11.4±2°	4.7±2°	15°	24°
		5	10.3±2°	5±0°		
534	Benzoic acid methyl ester	4	13±1°	9±0.4°	10°	25°
		4	14±0.8°	8±0°		
		4	9.9±0.3°	5.8±1°		
531	Benzoic acid ethyl ester	6	5.3±1°	4.6±1°	5°	25°
517	Benzoic acid butyl ester	4	10.5°	---	-	--
492	1,2-ethanediol diacetate	4	10±0°	5.3±0.5°	10°	25°
			5.9±3°	2.4±1°		
	HYDROCARBONS					
741	2,2,4-trimethylpentane	5	5.5±0.4°	2±0.4°	3°	25°
		3	8.3±0.6°	5.7±0.6°		
6781B	Pentane	3	14.7±2°	3.5±2°	7°	25°
733	Heptane	5	9.5±2°	3.8±0.8°	-	25!
		5	8.6±0.5°	4±0.4°		
740	Octane	5	9.4±0.9°	6.8±0.8°	10°	26°
		6	10±0.6°	7.5±2°		
756	1-octene	6	8.2±2°	6.8±2°	5°	25°
		6	9±1°	7.3±1°		
748	Cyclohexene	5	8.6±1°	8.4±0.5°	7°	25°
744	Decalin	6	16±1°	9.7±2°	15°	26°
	KETONES					
798	2-propanone	5	8.1±2°	1.8±1°	5°	24°
810	2-butanone	5	5.7±0.4°	2.8±1°	2°	23°

CONTACT ANGLES ON GLASS (cont.)

	KETONES (cont.)					
813	3-pentanone	6	7.6±0.8°	4.3±0.4°	2°	25°
		5	7.3±0.8°	3.5±0.6°		
811	2-octanone	5	7.7±0.8°	7.2±1°	5°	25°
		5	8.2±1°	6.3±0.4°		
5895B	4-methyl-2-pentanone	11	9.5±0.5°	6.1±1°	5°	26°
7121F	3,3-dimethyl-2-butanone	5	8.1±1°	3.4±0.7°	3°	26°
		5	9.2±0.4°	3.4±0.8°		
808	4-methyl-3-penten-2-one	5	6.4±2°	2.5±0.5°	2°	-
		5	5.7±0.8°	3.2±0.8°		
815	2,4-pentanedione	5	12.9±2°	11.8±3°	5°	27°
		4	12±4°	---		
	ALDEHYDES					
225	Butanal	5	9.6±2°	6.3±2°	5°	25°
		5	12.5±0.5°	8.1±0.5°		
234	Pentanal	4	13±0.8°	4.3±1°	5°	25°
231	Heptanal	4	14.8±2°	2.3±1°	17°	23°
		5	13.8±0.8°	1.3±0.7°		
240	Cinnamaldehyde	5	15.4±0.5°	6.8±1°	15°	-
	ETHERS					
172	Diethylene glycol monobutyl ether	5	14.6±0.5°	5.8±0.8°	12°	24°
		5	10.7±1°	4.8±0.4°		
8280	Triglyme	5	6.2±0.4°	3.6±0.5°	5°	25°
		5	6.4±0.7°	3.2±0.8°		
173	Diethylene glycol monoethyl ether	5	16.8±0.8°	6.3±0.6°	3°	-
		2	17.5±0.7°	5±0°		
3	Methylal	5	4±0.5°	2.4±0.5°	5°	25°
177	2-ethoxyethanol	5	6.7±0.4°	4.4±0.5°	2°	24°
221	2-phenoxyethanol	6	17.8±1°	10.5±2°	15°	25°
		5	17±1°	9.8±0.8°		
	AROMATICS					
764	Isopropylbenzene	5	15.6±0.5°	4±0.6°	2°	24°
		5	18.2±1°	7.9±0.7°		
771	1,3,5-trimethylbenzene	6	8.5±0.5°	7.8±2°	7°	-
		5	7.8±0.6°	7.2±2°		
	MISCELLANEOUS					
297	Triethylamine	5	9.4±2°	5.6±1°	5°	26°
856	1-nitropropane	4	9.8±0.5°	3±1°	3°	25°
		5	11.6±1°	3.6±0.5°		

CONTACT ANGLES ON GLASS (cont.)

	MISCELLANEOUS (cont.)					
7727F	Perhydrosqualene	6 6	18±0.9° 17.5±1°	13.5±1° 11.8±2°	20°	26°
6	2-methylpropanoic acid	5 5	13.9±1° 13.7±1°	4.4±0.8° 4.1±1°	7°	24°

Table 1. Contact Angles of Various Liquids on Glass

Chem Service No.--an identification number for each chemical
Liquid--name of liquid, and chemical family of liquid
#--number of measurements taken per pair of slides
$\gamma_{up} \pm \sigma$-- γ_{up} is the rising contact angle average for each pair of slides; σ is the standard deviation
$\gamma_{down} \pm \sigma$--γ_{down} is the receding contact angle average

$\gamma_{est.}$--the contact angle estimated by the droplet method

T--temperature in degrees Centigrade

All liquids are divided into families by chemical structure, and are ordered by chemical structure, i.e. the chemicals that are most similar chemically are next to each other.

*Since glycols are hygroscopic except for 2-methyl-2,4-pentanediol, only the first measurement taken is recorded for all other glycols.

CONTACT ANGLES OF VARIOUS LIQUIDS ON PLEXIGLASS *

Chem. Service No.	Liquid	#	$\gamma_{up} \pm \sigma$	$\gamma_{down} \pm \sigma$	$\gamma_{est.}$	T (°C)
	HALOGEN-SUBSTITUTED HYDROCARBONS					
618	2-bromopropane	3	23.7±2	9.3±1	-	25°
601	1-bromobutane	5	19.4±0.9°	5.6±0.4°	-	23°
		5	17.1±1°	5.6±0.7°		
666	Bromobenzene	5	14±4°	3.6±2°	-	26°
672	2-chlorotoluene	5	11.2±1°	6±0.7°	8°	25°
		5	12±1°	5.9±0.6°		
	ALCOHOLS					
142	1-butanol	5	17.5±1°	6.4±1°	5°	25°
		5	19.1±1°	7±1°		
139	1-pentanol	5	15.4±1°	6.6±1°	5°	25°
		5	15.5±1°	6.6±1°		
155	1-hexanol	5	18.6±1°	7.1±1°	-	24°
		5	18.4±2°	5.6±1°		
166	1-octanol	5	20.4±1°	5.7±1°	5°	24°
		5	21.4±1°	6.4±1°		
213	α-hydroxytoluene	5	18±2°	1.9±0.2°	-	25°
		5	19.4±2°	2.6±0.6°		
218	2-phenylethanol	5	12.6±1°	6±1°	-	-
		5	19.8±1°	6.4±1°		
	GLYCOLS*					
7990	2,2'-dihydroxydiethyl sulfide	-	37°	5°	40°	24°
195	Glycerin	-	67°	5°	60°	25°
	ESTERS					
2145B	Formic acid benzyl ester	3	21.7±2°	5.3±1°	15°	26°
		5	20.2±1°	6.2±0.8°		
412	Acetic acid ethyl ester	4	12.3±0.7°	4.3±1°	8°	26°
		3	17±3°	3.8±0.3°		
418	Propanoic acid ethyl ester	5	18.2±1°	4.9±0.7°	-	25°
		5	16.2±0.5°	5.4±0.6°		
1004	Propenoic acid butyl ester	5	9.1±0.8°	2.8±0.8°	5°	25°
		5	12.8±1°	6.2±1°		
4135B	Malonic acid dimethyl ester	5	23.2±2°	6.4±1°	28°	26°
		5	20.3±0.7°	6±1°		

*We were unable to measure the contact angle of water on plexiglass.

CONTACT ANGLES ON PLEXIGLASS (cont.)

	ESTERS (cont.)					
463	Malonic acid mono-ethyl ester mononitrile	5 5	13.2±1° 16.4±1°	4.6±2° 5.4±0.6°	-	25°
517	Benzoic acid butyl ester	5 5	16.1±0.7° 12.3±0.5°	6±0.4° 6±0.7°	-	25°
492	1,2-ethanediol diacetate	5 5	20.1±0.7° 22±2°	5.6±2° 6.2±2°	20°	26°
	HYDROCARBONS					
741	2,2,4-trimethyl-pentane	3 5	16±2° 17±2°	5.7±2° 5.4±1°	5°	26°
733	Heptane	5 5	23.8±0.8° 19.4±0.9°	8.6±1° 5.8±1°	2°	24°
740	Octane	5 5	9.8±0.6° 10.8±1°	2.4±0.6° 4.1±0.2°	-	26°
744	Decalin	5 5	14.3±0.7° 13.5±0.5°	4.4±0.6° 3.6±0.6°	8°	26°
	ALDEHYDES					
231	Heptanal	5 5	14±0.7° 13.3±1°	5.1±0.7° 4.9±0.9°	5°	26°
	AROMATICS					
764	Isopropylbenzene	5 5	12.6±2° 9.4±1°	5±1° 3.8±1°	4°	25°
	MISCELLANEOUS					
7727F	Perhydrosqualene	5 5	16.6±0.6° 15.5±1°	5.9±0.6° 5.4±0.9°	-	24°
6	2-methylpropanoic acid	5 5	18.2±3° 17.5±3°	4.4±1° 4.8±0.5	5°	25°