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A Review on Surface Tension Measurements by Optical Method for Medical Application

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Abstract— **Surface tension is a surface characteristic that is related to the forces of molecules residing at the interface. The presence of surface active substance in biological or body fluids which adsorb at interface influences the norm surface tension value. Such the changes indicate valuable signs in the medical field, particularly in pathological states. The conventional surface tension measurements suffered several flaws including lack of dynamic control and required a direct contact with the samples. The optical method seems to be attractive and useful in the surface phenomena owing to non-contact capabilities, non-destructive procedures and required a finite sample volume. In this paper, various optical techniques for surface tension measurement are reviewed and the potential applications regarding the surface tension through the meniscus formation are well discussed. This paper finds the simplicity and credibility of the optical method offers a good opportunity in fields such as medical and diagnostic analysis for monitoring applications.**

Keywords— **Surface tension measurements; Optical techniques; Non-destructive; Meniscus; Medical field.**

I. INTRODUCTION

Surface tension γ is a characteristic of any surface or interface and a cohesive force among liquid molecules in relation to the forces of molecules residing at or close to the interface. It is defined as the force acting perpendicular to the surface divided by the length of the surface measured in millinewtons (mN/m) or dynes per centimetre (dynes/cm). Matter at interfaces has different characteristics from that in the bulk of the media. Theoretically, the matter in bulk phase is attracted equally and the net force is balanced. In contrast to the matter at or near interfaces, they are influenced by a net of downward force due to absence of molecules at the surface. Consequently, the tension of the surface film gives rise to the surface tension. As one of the physical-chemical properties, surface tension plays an important role in natural phenomena [1]-[3]. Temperature, composition, presence of impurities, measurement time, materials of the apparatus, and viscosity are variables-dependent of surface tension in liquids. Surface active chemicals (surfactants) play a significant role in adsorption proses at the fluid surface. During this process, the surface tension changes rapidly and continuously, which can be monitored by the dynamic surface tension measurements. Upon the equilibrium process is achieved, the static surface tension measurement can be evaluated from the maximum force at the liquid interface [4]-[5]. Molecules and ions of surfactants adsorbing at interfaces leads to a reduction in surface tension and the adsorption is expressed quantitatively by Gibbs equation. The surface tension drops with the addition of surfactant until the interface achieves the saturation point, and the surface tension levels off [6]. In the case of two immiscible fluids, the term of interfacial tension is used instead of surface tension. If one or both liquids are surface active, the interfacial value is a time dependence which is important in the case of biological fluids because every biological possesses its own dynamic characteristic [7]. The methods for surface tension measurement have been reviewed and compared in [4][8]-[9]. Some of them involves the experimental techniques such as the direct measurement by force sensor, the study of drop [10]-[11] and the capillary force and pressure analysis [12]-[13]. The conventional measurements suffered flaws including lack of dynamic control and required a direct contact with the sample. Therefore, the optical method offers an alternative method that use light to probe as it provides simple, reliable and repeatable method to study the surface phenomena [14]-[15]. It is interesting to note that, practically, the goal of optical techniques is often times to determine changes in surface tension rather than obtaining absolute values.

II. SURFACE TENSION IN HUMAN FLUID

Human body fluids are regarded as desirable sources for biological markers and are one of the most promising approaches in disease diagnosis and prognosis [16]. The study of surface tension in human biological fluids started in 1911 [17] and its relationship to the development of disease have been closely observed through the surface tension changes in several experiments on body fluids (see Table I) to a point that the surface tension concept might be a potential tool in medical diagnostics [7][18]. The surface tension changes of biological phenomena and the failure of biological fluids to maintain their normal state will provide additional useful information in medical practice. Thus, surface tension data are helpful for diagnostic purposes and monitoring treatment efficacy.

TABLE I
SURFACE TENSION CHANGES IN BODY FLUIDS

Body Fluids	**Surface Tension (mN/m)**		**Reason**	**Ref**
	Normal	**Changes**		
Saliva	46.0 ± 0.70	43.1 ± 1.0	Caries	[19]
Urine	58.7 ± 2.16	Bile salt content	Bile salt	[20]
Blood	55.89 ± 3.57	Temperature	Thermal body	[3] [21]
Infant airways	6.3 ± 1.1	35.0 ± 1.4	RSD	[22]

From Table I, the surface tension of saliva for caries-active children was found to be 3 mN/m lower than that for caries-free children. This significant difference is due to the high surfactant amount in the oral liquid of caries-free children, which is important for the estimation of tooth enamel decay. The presence of bile salt in normal urine was reported to decrease the surface tension value [23]-[24] at which the work of [19] revealed an inverse relationship between total bile salt concentrations and surface tension values through radioimmunoassay and spectrofluorimetric assay. This inverse relationship existed from 70 to 54 mN/m for both normal urines. It was also reported that the role of urinary constituents is not dominant in determining surface activity of urine because the surface tension did not change too much. Furthermore, the study of surface tension in blood had been reported in [25]-[27]. The works suggested the surface tension of the blood is affected by the pathological diagnosis and denaturation effect in the blood protein with thermal effect. As adapted in [21], the importance of blood's surface tension is in the formation of blood clots in where it affects the bleeding characteristics and the occurrence of the decompression sickness by the formation of gas bubbles and the drug administration. Moreover, [28]-[30] investigated the surface tension of tears fluid which providing an insight to a new application in the development of contact lens and the evaluation of patients with dry eyes due to the fact that the formation and stability of the film in both health and disease depend on the physical properties of the tears including surface tension. In infant respiratory system, the neonatal respiratory distress syndrome (RDS) [22] is a disease caused by lung immaturity and surfactant deficiency in the alveolar space results a high surface tension value. Hence, it can be concluded that the tensiometric measurement can potentially be used as new diagnostic criteria in the medical field for the estimation of abnormalities in surface tension of body fluids.

III. TECHNIQUES FOR SURFACE TENSION

The optical technique for surface tension has emerged from surface light scattering to study excited capillary waves at which the wave amplitude from the wave profile through generation of capillary wave packet by excitation and detection of wave signal by transducer and confocal optical microscope, respectively. The calculated and unwrapped wave phase from the wave signal is subjected to Kelvin's dispersion equation for the evaluation of surface tension [31]. Meanwhile, [32] investigated the wave's shift of resonant peak frequency of through a single focused beam quasi-elastic light scattering experiment by applying Lamb's equation. This method's utilization of 2D capillary waves requires only a single focused beam for microscale analysis compared to conventional method, which need two beams and thus causes many limitations. The shifted wave corresponds to the frequency of capillary wave is obtained from the scattered light of liquid interface after fitting them into a spectrum analyser. The method's applicability is successfully demonstrated for surface tension measurement of surfactant solution. In the work of [33], the capillary waves serve as reflective grating resulting the formation of destructive and constructive interference patterns at which the reflected angle of light from the grating surface reflection is not equal to the initial incident angle. The surface tension is obtained by applying the dispersion equation from the calculated wavelength of capillary waves through the measurement of known incident angles and the measured diffraction angles, yielding the needed wavenumbers for the independent values of surface tension. The surface tension measurement is performed by inserting all the experimental values involved into the software for further calculation.

To date, the advancement in fiber optic sensing technology [34]-[35] based on the light guiding concept in the fiber have been developed for surface tension analysis. The scattered light was compared [36] and mixed [37] with the local oscillator using the fiber optic system. The homodyne detection compared the signal with a standard oscillation while the heterodyne detection mixed the signal with the local oscillator resulting a frequency of mixing product to obtain the selective wave vectors from the spectrometer. The weak scattered signal is enhanced by amplification in accordance to properly match of polarization signals, at which the deduced surface tension is obtained from the autocorrelation function by applying the dispersion equation. The measured surface tension value with deviation of less than 1% is achieved, however, this setup cannot operate for opaque liquids. Moreover, the sensor concept of bubble formation in a microchannel is demonstrated using a small setup of optical detection system. The changes in laser intensity are detected when the bubbles passing through a detection point between two optical fibres and crossing each other. The detection point is formed when a sample from the main channel meets a sample from the small channel at the T-junction and the bubble formation occurs. The resulting generated pulse of bubble signals from the mixed samples showed a dependency on their formation frequency which is inversely related to the surface tension [38]-[39]. The frequency values increase when surface tension changes from 0.0725 N/m to 0.0386 N/m for 4 ml/h - 8 ml/h sample flow rates of different concentration surfactant solution.

Interestingly, the setup is also capable in detecting the critical value in surface tension through the indication of sharp frequency changes, which is crucial in determining the optimal and effective value for certain applications.

The work on fiber interferometry have been extensively done due to its high resolution, great precision and stability measurement. In interferometry, the combination of measurement waves and reference waves produces a shift in the interference fringe pattern [40]. A reflected laser light from the cleaved tip of the fiber and the fluid surface travel back through the same fiber and generate an interference signal at the detector. The surface tension is analysed by monitoring and counting the number of fringes in the periodic interference signal from the fiber tip - fluid surface gap as the fluid level under the probe changes due to the wave motion through the electronically generation of standing capillary waves. The number of fringes gives an accurate measure of the wave amplitude and the surface tension is then extracted from the dispersion data. Comparing to conventional methods, this technique required no correction factors, however it is only suitable for polar liquid since the capillary wave is electronically generated [41]. On the other hand, [42] proposed a combination surface tension sensor of the spliced - hollow fiber for measuring surface tension by contacting the hollow fiber end face with the liquid sample. The changes in wavelength spacing variation of generated interference pattern from the reflection of the air-liquid interface and spliced fiber interface created by an enclosed air cavity as a result of capillary effect has shown the varied wavelength spacing from 3.580 to 5.897 nm when surface tension was increased from 0.02255 N/m to 0.09676 N/m. Having an advantage in measuring the surface tension directly by deriving own equation for the combination setup, unfortunately this sensor cannot operate for corrosive liquid due to the possibility in damaging the probes when being in-contact. Moreover, [43] showed the phase shifting of droplet hanging at the end-spliced fiber by using a low-coherence interferometer implying the inverse relationship between droplet's thickness and surface tension of different liquids at which the thickness of the droplet is larger for lower surface tension. This technique is highly sensitive as the thickness fluctuations are a fraction of nanometre, but it faces several difficulties, including changes in droplet's profile and small droplet's fluctuation could affect the thickness measurements

Furthermore, drop formation from fiber dipping plays a crucial role in showing the surface tension concept. This is proven by [44]-[45] through drop formation of fiber. Required only small sample volume is an advantage, but gave to incorporate with the CCD unit in order to capture the surface liquid profile and drop image, which is costly. The former introduced a fitted model at which the signal patterns formed due to the refractive indices between the cleaved end fiber and the liquid revealed that the larger the drop height corresponds to a larger value of surface tension. Whereas, the latter used fiber capacitive drop method by dipping the fiber probe vertically into the liquid sample. The shape of the drop formed after the fiber is pulled out influences the light transmission path. Thus, the surface tension can be expressed by the geometrical parameters of the drop. The optical techniques in surface tension are summarized in Table II and their respective strengths and weaknesses are tabulated in Table III.

TABLE II
OPTICAL TECHNIQUES FOR SURFACE TENSION

Experimental Technique	**Monitoring Parameter**	**Evaluation**	**Ref**
Broadband excitation	Wave amplitude	Kelvin's dispersion	[31]
Frequency's shifting	Wave frequency	Lamb's equation	[32]
Reflective grating	Wavelength, wave-number	Kelvin's dispersion	[33]
Waves amplification	Wave vector	Kelvin's dispersion	[36] [37]
Bubble formation	Frequency formation	Frequency increases corresponds with 0.0725 N/m to 0.0386 N/m	[38] [39]
Standing capillary wave	Period change in path difference	Fringes counting and extracting the surface tension value from dispersion data	[41]
Interface reflection	Wavelength spacing	Vary from 3.580 nm to 5.897 nm with 0.02255 N/m to 0.09676 N/m	[42]
Droplet's fluctuation	Phase shifting of droplet	Droplet's thickness changes with surface tension: 83 nm (0.02239 N/m) 54 nm (0.0728 N/m) 47 nm (0.1067 N/m)	[43]
Drop formation	Drop height	Drop height changes with surface tension: 38.29 μm (0.0211 N/m) 38.85 μm (0.0212 N/m) 38.88 μm (0.0215 N/m) 42.95 μm (0.0625 N/m)	[44]
Drop formation	Drop shape	Geometrical parameters of the drop by analysing the light signals	[45]

TABLE III
STRENGTHS AND WEAKNESSES OF SELECTED OPTICAL TECHNIQUES

Experimental Technique	**Strengths**	**Weaknesses**	**Ref**
Bubble formation	Potential to detect critical value of surface tension	Small setup and fine channels lead to measurement errors	[38] [39]
Standing capillary wave	Required no correction factors	Only for polar fluids	[41]
Interface reflection	Capable of measuring surface tension directly	Cannot be used for corrosive liquids	[42]
Droplet's fluctuation	Highly sensitive (thickness fluctuations in nm)	Changes in droplet's profile can affect results	[43]
Drop formation	Required a finite sample volume (pL)	Complicated model and has numerous raw data	[44]
Drop formation	Technically easy to conduct	Required CCD unit which is costly	[45]

IV. MENISCUS POTENTIAL APPLICATION

The meniscus is the curve in the upper surface of a liquid close to the surface container caused by surface tension. The meniscus resulted from cohesion and adhesion force can be either concave or convex depending on the liquid and the surface [46]. This can be observed in the case of capillary effect at which a contraction in surface film forming a meniscus due to liquid attraction to the surface container until the adhesion force is balanced [47]-[48]. Interestingly, Young equation related the surface tension to the contact angle at which the value of contact angle determines the curvature of the meniscus. The contact angle is a measure of the wettability of a solid by a liquid. The equation indicates when θ=90°, the meniscus is flat; when θ<90°, the meniscus is curved upward; and when θ>90°, the meniscus is curved downwards [49]. Due to difference in contact angle, the curvature differed. Therefore, the formation of meniscus has a relationship with the surface tension and contact angle. The Young equation is given as:

$$\gamma_{lv}\cos\theta = \gamma_{sv} - \gamma_{sl} \tag{1}$$

Where γ_{lv}, γ_{sl} and γ_{sv} are the liquid–vapor contact line to the surface tension of the liquid, the solid–liquid and solid–vapor interfacial tension, respectively.

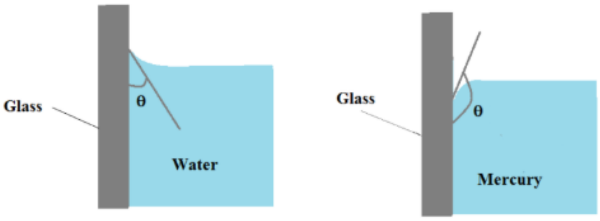

Fig. 1 Meniscus and contact angle relationship at glass wall

In optical study, [50] determined the surface tension through the pressure generated of meniscus deformation by placing a liquid in a horizontal capillary in front of the optical system. The corresponding pressure data obtained varies in the range from ±0.5 to ±5 Pa were used for calculation of the surface tension. In other work, the percentage of the optical density decreased because of the pathlength difference in meniscus formation as compared to no meniscus formation. This showed that the meniscus formation at the liquid interface introduced a significant variability into the measurement of optical density. The pathlength with the presence of meniscus seem to be shorter because of the inward contraction on the surface [51]. [52] suggested that the difference in pathlength occurred due to the meniscus is affected by the concentration and the buffer composition of the measured sample. They potentially altered the pathlength even the sample volume stays per same because the physical characteristics (surface tension, polarity, etc.) of the solution affect the meniscus formation. Cottingham investigated the surface tension through the ability of meniscus to act like a lens by measuring the relative intensity of a passing beam light through liquid [49]. The lower the value of the contact angle, the greater the curvature of the meniscus and the lower the intensity of the light detected because the light losses became more dominant with the greater curvature. The light intensity varies as a function of the contact angle of the liquid and the side of the vessel, which is in turn related to surface tension. However, this method is still limited to determination of relative surface tension, since there is no absolute correlation between the apparent optical density and the surface tension. The curved liquid surface also has a capability to reflect the light by critical [53] and boundary [54] reflection principle at which the relation between the reflective patterns and the curved liquid surface was analyzed. In the work of [53], the special reflective patterns containing a dark central region and a bright field outside formed provide the information on the surface maximal height and the curved surface profile. The method is improved by [54] to measure the slope and the height of curved surface at any point and the analytic expression of the curved surface profile is derived by vertically illuminated the light on the curved liquid surface. Thus, the curved liquid surface has proven to be able to undergo reflection and for the measurement of characterization of curved liquid surface. Hence, it can be concluded that the meniscus has shown several potential abilities in optical method and can be utilized for new measurement to the study of surface tension

V. FUTURE DEVELOPMENT IN MEDICAL

Surfaces are critically important for nearly all aspects of biological phenomena. The surface tensiometry is a sensitive method which can reveal subtle changes in the content of biological fluids. Thus, there is an opportunity of the tensiometric measurements as a diagnostic tool in medical application and monitoring device in the treatment efficacy. By developing the optical technique to study the surface tension will make a step further in preliminary diagnostics as the optics have been proven a powerful technology in the study of light behaviour and its manipulation in detection area.

VI. CONCLUSIONS

The study of surface tension in human fluid shows that the measurement of surface tension is important in medical application, particularly in the diagnostic area, whereby it potentially can be regarded as a significant tool for extinguishing pathological status. This is due to various diseases influence the composition and interfacial tension of body fluids. The present paper is devoted to a review of the optical techniques in surface tension measurements and the potential application of meniscus as a new alternative for surface tension measurements. Some of the optical techniques are able to measure surface tension directly, however, encountered limitations for the probes and the sample whereby the probes had to be spliced in order to obtain the measurements and dipped into the sample, which might not suitable for corrosive and high purity liquids even they required only finite sample volume. The meniscus formation, which is closely related to surface tension provides an insight to a new technique due to its potentiality and ability to act like lens and reflect the light which implies its usefulness in optical method. For future development, this paper highlights the needed for a simple contactless optical technique for investigation of meniscus formation in liquid surface concerning that the study of surface tension is a useful discovery for medical application.

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