

University of Alberta

**The Effect of Surfactants on Microscale Wave Breaking and
the Aqueous Boundary Layer**

by

Mohamed Khairy Mohamed El Kamash

A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfillment of the requirements for the degree of Doctor of Philosophy

in

Water Resources Engineering

Department of Civil and Environmental Engineering

Edmonton, Alberta

Spring 2005

Acknowledgements

I am grateful to my supervisor Professor Mark R. Loewen for his great support and help. He started me off on the right way, provided academic guidance and encouragement, introduced me to much of the materials in the thesis, offered his time to discuss the development and progress of the thesis and learned me a lot throughout the course of my research. He also supported me financially, supported my conference presentations and my visit to the University of Washington to carry out my experimental work.

During my PhD program, many people have helped me. Dr. Kamran Siddiqui provided me with a lot of his experience in the field of my work as well as computer algorithms related to much of the materials in the thesis. Dr. William Asher and Dr. Andrew Jessup at the University of Washington allowed me to carry out my experiments, helped and guided me as well. Dr. Mohamed Atmane assisted me with the IR measurements, provided me with the bulk gas transfer results and offered his time to discuss some of my results.

I gratefully acknowledge the excellent atmosphere surrounded my research by all the staff, colleagues and friends in the water resources group. My heartfelt thanks are also extended to my parents, family and friends for their continued encouragement and support. And last but not least, thanks to my wife for her never-ending support, confidence and love.

I gratefully acknowledge the support of the University of Alberta, National Science and Engineering Research Council (NSERC) and Alberta Informatics Circle of Research Excellence (icore) in the form of postgraduate scholarships.

Abstract

This study reports on a laboratory investigation of the effect of surfactants on the properties of the aqueous boundary layer, the properties of microscale-breaking waves, the characteristics of coherent structures and the air-water gas transfer velocity rates. Digital particle image velocimetry and surface wave profile measurements were gathered for clean and surfactant-influenced water surfaces. At all wind speeds (3.8 to 9.8 m·s⁻¹) the flow in the aqueous boundary layer was found to be in the transition regime for both water surface conditions.

The fraction of the total vertical momentum transferred to the aqueous boundary layer decreased from 0.65 to 0.15 for clean water surfaces and from 0.7 to 0.3 for surfactant-influenced water surfaces as the wind speed increased from 3.8 to 9.8 m·s⁻¹. A strong negative correlation was observed between the fraction of the total momentum transferred to the aqueous boundary layer and the mean square wave slope irrespective of water surface condition.

The ratio of the rate of dissipation of turbulent kinetic energy in surfactant-influenced water, to that in clean water decreased from 1.0 to 0.70 as the wind speed increased from 3.8 to 9.6 m·s⁻¹. A surfactant reduced the thickness of the enhanced layer of near-surface turbulence on average by 35%. The surfactant reduced the percentage of wave breaking by approximately one third and reduced the wave amplitude and the maximum wave slope on the forward face of the waves by an average factor of 25% and 28%, respectively for breaking waves and 22% and 19%, respectively for non-breaking waves. A strong correlation was observed between the fraction of the total momentum

transferred to the wave field and the percentage of breaking waves irrespective of the water surface cleanliness.

The frequency of occurrence of coherent structures increased by a factor of ~10 for both clean and surfactant-influenced water surfaces as the wind speed increased from 3.8 to 9.6 m·s⁻¹. The surfactant reduced the frequency of occurrence of coherent structures by approximately 20% and the measured bulk gas transfer velocities by approximately 55%.

Table of Contents

1 Introduction	1
2 Aqueous Boundary Layer and Momentum Transfer	
2.1 Introduction.....	6
2.2 Experimental Setup.....	10
2.2.1 Instrumentation and Methods.....	10
2.2.2 Experimental Procedures.....	15
2.3 Results.....	20
2.3.1 Wave Properties.....	20
2.3.2 Surface Drift Velocity.....	21
2.3.3 Airside Friction Velocity.....	22
2.3.4 Aqueous Boundary Layer.....	23
2.3.4.1 Mean Velocity Profiles.....	23
2.3.4.2 Velocity Defect Law.....	25
2.4 Discussion.....	28
2.5 Conclusion.....	41
3 Near-Surface Turbulence and Microscale-Breaking Waves	
3.1 Introduction.....	64
3.2 Bulk Gas Transfer Velocities.....	72
3.3 Rate of dissipation of Turbulent Kinetic Energy.....	73
3.3.1 Spectral Analysis.....	73
3.3.2 Turbulent Kinetic Energy Dissipation Calculations.....	74
3.4 Discussion: Turbulent Kinetic Energy Dissipation.....	79
3.5 Microscale-Breaking Waves.....	83
3.5.1 Detection Scheme.....	83
3.5.2 Microscale-Breaking Wave Characteristics.....	88
3.6 Discussion: Microscale-Breaking Waves.....	91
3.7 Conclusions.....	100
4 Coherent Structures and Air-water Gas Transfer	
4.1 Introduction.....	133

4.2 Near surface vorticity.....	138
4.3 Coherent Structures Identification Technique.....	139
4.4 Characteristics of Coherent Structures.....	143
4.5 Air-Water Gas Transfer.....	149
4.5.1 Surface renewal model.....	149
4.5.2 Air-Water Gas Transfer Results.....	155
4.6 Conclusions.....	160
5 Conclusions and recommendations	
5.1 Summary and Conclusions.....	180
5.2 Recommendations for Future Work.....	183
References.....	186
Appendix A.....	196
Appendix B.....	204

List of Tables

Table 2.1: Summary of environmental parameters for both water surface conditions.....	44
Table 2.2: Summary of velocity measurements for different experimental runs for both water surface conditions.....	45
Table 2.3: Summary of velocity defect law results for both water surface conditions.	46
Table 3.1: Comparison between the rates of turbulent kinetic energy dissipation computed using three different methods for clean water surface runs.....	102
Table 3.2: Depth-averaged rate of energy dissipation values for the top 2 cm water for both water surface conditions.....	103
Table 3.3: Values of the vorticity variance threshold and numbers of detected microscale-breaking waves from different methods.....	104
Table 4.1: Summary of the characteristics of coherent structures for both water surface conditions.....	163
Table 4.2: Summary of air-water gas transfer velocity results for both water surfaces conditions.....	164

List of Figures

FIGURE 1.1: Sketch illustrating the conceptual model of a microscale-breaking wave	5
FIGURE 2.1: Schematic of the experimental setup illustrating the instrumentation used in the wind wave tank.....	47
FIGURE 2.2: A flow chart showing the synchronization of the IR, profile and DPIV cameras and the laser.....	48
FIGURE 2.3: A typical profile image obtained from the profile camera at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$ with the computed water surface profile plotted on top of it as a white line.....	49
FIGURE 2.4: A typical DPIV image with the water surface profile plotted on top of it as a white line.....	50
FIGURE 2.5: The two-dimensional instantaneous velocity field.....	51
FIGURE 2.6: Infrared image showing a heated patch generated by the CO_2 laser.....	52
FIGURE 2.7: Plot of the ratio of the surface velocity U_s to the wind friction velocity u_{*a} for various wind speeds.....	53
FIGURE 2.8: Vertical profiles of the stream wise component of the mean velocity. (a) Clean water surfaces, (b) Surfactant-influenced water surfaces.....	54
FIGURE 2.9: Vertical profiles of the stream wise component of the mean velocity for clean and surfactant-influenced water surfaces.....	55
FIGURE 2.10: The mean streamwise velocity plotted in the form of a velocity defect law in wall coordinates. (a) Clean water surfaces, (b) Surfactant-influenced water surfaces.....	56
FIGURE 2.11: Plots of the shear stresses for various wind speeds.....	58
FIGURE 2.12: Plot of the ratio of the waterside shear stress to the airside shear stress at various wind speeds.....	59
FIGURE 2.13: Plot of the ratio of the waterside shear stress to the airside shear stress versus the mean square wave slope of the waves.....	60

FIGURE 2.14: Plot of the ratio of the shear stress ratio versus the wind speed. Different sets of data were compiled from the literature as labeled in the figure.....	61
FIGURE 2.15: Plot of the ratio of the shear stress versus the steepness.....	62
FIGURE 2.16: Plot of 1- the ratio of the waterside shear stress to the airside shear stress versus the mean square wave slope of the waves.....	63
FIGURE 3.1: Plot of the bulk gas transfer velocity for various wind speeds.....	105
FIGURE 3.2: Plot of the bulk gas transfer velocity versus the mean square wave slope.....	106
FIGURE 3.3: Longitudinal wave number spectra of the streamwise instantaneous velocity component, at five wind speeds for clean water surface runs.....	107
FIGURE 3.4: Comparison of the longitudinal wave number spectra of the streamwise instantaneous velocity component for clean and surfactant influenced water surfaces.....	108
FIGURE 3.5: Vertical profiles of the rate of energy dissipation at different wind speeds (a) Clean water surfaces, (b) Surfactant-influenced water surfaces.....	109
FIGURE 3.6: Vertical profiles of the rate of energy dissipation, ε , for clean and surfactant influenced water surfaces.....	110
FIGURE 3.7: Plot of the dimensionless rate of energy dissipation versus the dimensionless depth for both water surface conditions.....	111
FIGURE 3.8: Plot of the dimensionless rate of energy dissipation versus the dimensionless depth using wall layer scaling (a) Clean water surfaces, (b) Surfactant-influenced water surfaces.....	112
FIGURE 3.9: Plot of the mean square wave slope versus the depth averaged rate of energy dissipation over top 2-cm layer.....	113
FIGURE 3.10: (a-c) A sequence of paired plots of an instantaneous vorticity field (top) and IR image (bottom) showing a non-breaking waves at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$	114
FIGURE 3.11: (a-c) A sequence of paired plots of an instantaneous vorticity field (top) and IR image (bottom) showing a microscale-breaking waves at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$	117

FIGURE 3.12: Plot showing the instantaneous vorticity field beneath a wave crest at wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$. The region of interest (ROI) is marked with dashed-lines.....	120
FIGURE 3.13: The percentage of microscale breaking waves P_b versus wind speed.....	121
FIGURE 3.14: Plot of the maximum wave slope on the downwind face of the wave versus wind speed for clean and surfactant influenced water surfaces. (a) Microscale breaking waves, (b) Non-breaking waves.....	122
FIGURE 3.15: Plot of the maximum wave amplitude versus wind speed for clean and surfactant influenced water surfaces. (a) Microscale breaking waves, (b) Non-breaking waves.....	123
FIGURE 3.16: PDF's of the maximum wave slope on the downwind face of the waves at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$ for a clean water surface for microscale breaking waves and non-breaking waves.....	124
FIGURE 3.17: PDF's of the maximum wave amplitude at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$ for a clean water surface for microscale breaking waves and non-breaking waves.....	125
FIGURE 3.18: PDF's of the maximum wave slope on the downwind face of the waves at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$ for microscale breaking waves for clean and surfactant influenced water surfaces.....	126
FIGURE 3.19: PDF's of the maximum wave amplitude at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$ for microscale breaking waves for clean and surfactant influenced water surfaces.....	127
FIGURE 3.20: Vertical profile of the rate of energy dissipation at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$ under non-breaking waves, microscale-breaking waves, entire flow field and background flow field. (a) Clean water surface, (b) Surfactant influenced water surface.....	128
FIGURE 3.21: Vertical profiles of the rate of energy dissipation beneath microscale-breaking waves. (a) Clean water surface, (b) Surfactant influenced water surface.....	129

FIGURE 3.22: Plot of the mean square of the maximum wave slope on the downwind face of the waves versus the rate of energy dissipation averaged over top 2-cm layer for clean and surfactant influenced water surfaces.....	130
FIGURE 3.23: Plot of the fraction of the total momentum transferred to wave drag versus the percentage of microscale breaking waves P_b , for clean and surfactant-influenced water surfaces.....	131
FIGURE 3.24: Plot of the bulk gas transfer velocity, k_G versus the percentage of microscale breaking waves P_b , for clean and surfactant-influenced water surfaces.....	132
FIGURE 4.1(a-d): A sequence of four DPIV instantaneous vorticity contour plots at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$	165
FIGURE 4.2: Plot showing the coherent structures identified by applying the vorticity threshold to the raw instantaneous vorticity field (i.e. no interpolation) at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$	167
FIGURE 4.3: (a) Contours of the instantaneous vorticity beneath the crest of a microscale-breaking wave at a wind speed of $9.6 \text{ m}\cdot\text{s}^{-1}$. (b) Plot showing the coherent structures identified by applying the vorticity threshold on the instantaneous vorticity field shown in panel (a). Vorticity data was interpolated by a factor of 4.....	168
FIGURE 4.4: Probability density function (PDF) of λ , the nominal size of the coherent structures at wind speed of $3.8 \text{ m}\cdot\text{s}^{-1}$, (a) no interpolation and interpolating by a factor of 4. (b) interpolating by a factor of 24 and a factor of 4.....	169
FIGURE 4.5: Probability density function (PDF) of λ , the nominal size of the coherent structures for different wind speeds. (a) clean water surfaces, (b) surfactant-influenced water surfaces.....	170
FIGURE 4.6: Probability density function (PDF) of the maximum vorticity of the coherent structures at different wind speeds, positive values are the counter clockwise vortices and negative values are the clockwise vortices. (a) Clean water surfaces, (b) surfactant-influenced water surfaces.	171

FIGURE 4.7: The total kinetic energy of coherent structures versus wavenumber ($k=2\pi/\lambda$) at different wind speeds. (a) For clean water surfaces, (b) for surfactant-influenced water surfaces.....172

FIGURE 4.8: Comparison between the total kinetic energy of coherent structures versus wavenumber at a wind speed of 9.6 m.s^{-1} for clean and surfactant-influenced water surfaces.....173

FIGURE 4.9: Plot of the average length scale of the coherent structures as a function of wind speed for clean and surfactant-influenced water surfaces.....174

FIGURE 4.10: Plot of the average maximum vorticity of the coherent structures versus wind speed for clean and surfactant-influenced water surfaces.....175

FIGURE 4.11: The frequency of occurrence of coherent structures versus wind speed for clean and surfactant-influenced water surfaces.....176

FIGURE 4.12: The total air-water gas transfer velocity normalized to a Schmidt number of 600, versus wind speed for clean and surfactant-influenced water surfaces.....177

FIGURE 4.13: Measured bulk gas transfer velocity normalized to a Schmidt number of 600 versus the fraction of the surface area renewed by eddies for clean and surfactant-influenced water surfaces.....178

FIGURE 4.14: The percentage of microscale-breaking waves versus the fraction of the surface area renewed by eddies for clean and surfactant-influenced water surfaces.....179

List of Symbols

a	Wave amplitude.
a_1	Constant.
C_1	Constant.
C_2	Constant.
C_r	Roughness constant.
D	Molecular diffusivity of the gas in the liquid.
$D(k)$	Dissipation spectrum.
f_{CO_2}	Frequency of CO ₂ pulses.
f_{CS}	Frequency of occurrence of coherent structures.
f_d	Dominant intrinsic wave frequency.
$F(\omega)$	Energy spectrum of the wave amplitude time series.
g	Gravitational acceleration.
H_{rms}	Root mean square (RMS) wave height.
H_s	Significant wave height.
k	Wavenumber.
k_e	Gas transfer velocity inside the energetic areas.
k_G	Gas transfer velocity.
k_{me}	Wavenumber of the most energetic coherent structures.
k_q	Gas transfer velocity inside the quiescent areas.
KE	Kinetic energy of coherent structures.
n	Constant.
N	Constant (threshold factor).
N_{DS}	Number of microscale-breaking waves identified by the detection scheme.
N_{FN}	Number of falling negative waves.
N_{FP}	Number of falling positive waves.
N_V	Number of microscale-breaking waves identified by IR visual inspection.
N_c	Number of microscale-breaking waves identified by both schemes.
P	Probability density function.
P_b	Percentage of breaking waves.

R	Longitudinal spatial correlation.
Re^*	Roughness Reynolds number.
S	Wave slope.
S_c	Schmidt number.
S_M	Maximum mean shear.
S_{max}	Maximum wave slope.
S_{rms}	Root mean square (RMS) wave slope.
T	Top width of coherent structures.
T_m	Mean top width of coherent structures.
T_{skin}	Water skin temperature.
T_{thres}	Threshold temperature.
u	Instantaneous stream wise velocity.
\bar{u}	Mean stream wise velocity.
u'	Turbulent stream wise velocity.
u^*_{*a}	Friction velocity in the air.
u^*_{*w}	Friction velocity in the water.
u^+	Non-dimensional stream wise velocity in the universal wall coordinates.
\tilde{u}	Wave-induced velocity component.
U_∞	Wind speed.
U_s	Surface velocity.
U_{SL}	Lagrangian surface drift velocity.
U_{stokes}	Stokes drift velocity.
$U(z)$	Mean wind velocity.
w'	Vertical turbulent velocity component.
X	Horizontal coordinate.
Y	Longitudinal coordinate.
z	Vertical height above the interface.
z_{oa}	Roughness length in the air.
z_{ow}	Roughness length in the water.
α	Constant.
Δy	Difference in the y coordinate.

Δt	Time interval between the images.
η	Kolmogorov length scale.
η_{max}	Maximum wave amplitude.
ε	Rate of turbulent kinetic energy dissipation.
ε_{av}	Depth averaged rate of turbulent kinetic energy dissipation.
Φ	Fraction of the surface occupied by energetic areas.
Φ_u	Wave number spectrum of the stream wise velocity.
γ_t	Fraction of time.
κ	Von Karman constant.
λ	Nominal size of coherent structures.
λ_d	Dominant wavelength.
λ_{me}	Nominal size of the most energetic coherent structures.
μ	Dynamic viscosity.
ν	Kinematic viscosity.
ρ_a	Air density.
ρ_w	Water density.
σ_T	Standard deviation.
τ	Characteristic timescale.
τ_a	Shear stress in the air.
τ_w	Shear stress in the water.
τ_v	Viscous shear stress.
ω	Radian frequency.
ω_{max}	Maximum vorticity of coherent structures.
ω_b	Mean value of the background vorticity.
Ω	Angular velocity of an eddy.
Ω_{max}	Maximum vorticity variance.
ζ	Water depth in the wave-following coordinate system.
ζ^+	Non-dimensional water depth in the universal wall coordinates.