Chapter 1
Introduction

1.1 Objectives

The maritime transport industry carries the majority of global trade. Large ships and tankers are powered by heavy duty, low to medium speed diesel engines. These types of marine diesel engine are the most efficient internal-combustion engines in the world, capable of delivering greater than 50% thermal efficiency. A typical low speed marine diesel engine has a high reliability rate with 80% availability. The engine is capable of operating with very low quality, heavy fuel oil (HFO) composed mainly of residue from crude oil refineries with approximately one-third cutter-stock added to dilute the residue. The combination of high reliability, low running cost and high efficiency allows major trading economics to thrive with minimal transport costs.

While ship diesel engines tend to be very fuel efficient, their oxides of nitrogen (NOx) emissions are inherently high, due to the relatively long combustion duration [1]. Ship engine exhaust emissions contribute significantly to air pollution over land [2, 3]. Reducing flame temperature can reduce NOx emissions at the expense of increased fuel consumption and soot emissions. Today’s crude oil refinery technology has improved greatly, turning the raw material into valuable products including fuel. Moreover, the demand for fossil fuel is higher than ever before and this drives the crude oil refinery to continuously improve its refining capability. The main composition of HFO is residue left over from the processed crude oil. The efficient refining technologies result in increasingly poorer quality residues from the crude. Poor quality fuel results in poor combustibility of the HFO and with delays in ignition. As a result, the engine is more likely to be damaged and the lifespan of engine components are reduced. These problems of engine reliability, poor quality fuel and environmental damage led to the formation of this project.

Design of diesel engines utilises CFD for optimisation of spray patterns and combustion chamber geometry. This project aims to improve the accuracy of the CFD modelling of the spray dynamics, in the absence of evaporation and combustion. This allows the primary spray
formation processes to be studied in relative isolation. The aim is to contribute to improved
engine design for increased engine efficiency and reduced emissions of NOx and soot.

Engine designers generally use the Lagrangian/Eulerian approach whereby the spray particles
are tracked in a Lagrangian frame of reference, while interacting with the background fluid
which is modelled in a Eulerian frame of reference. This leads to much reduced computational
loads compared with a two phase fully Eulerian approach. Reynolds Averaged Navier Stokes
(RANS) turbulence models for the background fluid have been the primary choice in CFD
simulation of diesel sprays. The various sub-models which are used quantify diesel spray
behaviour have been developed in the context of RANS turbulence models. RANS models are
unable to capture the instantaneous spray structure including droplet clustering and shot to shot
variability. The use of Large Eddy Simulation (LES) as the turbulence model for the
background fluid promises to overcome these limitations. This project thus investigates the
behaviour of the various spray sub-models with LES and at least qualitatively examines the
extent to which LES allows the instantaneous spray structure to be well represented. This
project is not about how best to do LES, but rather how an established LES code behaves in the
diesel spray modelling context.

Literature reviews have shown there are many publications on the topic of high speed diesel
engines. Publications related to low and medium speed marine diesel engines are rare. High
speed diesel engines used in automotive applications consume light diesel fuel. The diesel
injection duration is usually one to two milliseconds and each combustion chamber has a
volume between 500 mL and 1000 mL. These engines have an operating speed between 2000
rotations per minute (RPM) and 4000 RPM. Light diesel fuel normally contains a high
percentage of light components with low sulphur content and low viscosity. The spray vaporises
quickly which results in short penetration. There is negligible influence of fuel viscosity on the
breakup process and the primary effect on the droplet breakup is liquid surface tension. A single
component fuel with relatively linear physical properties such as density, viscosity and
vaporisation rate, is normally used in the numerical simulation of light diesel fuel sprays.

The automotive diesel spray studies can not be applied in the simulation of HFO sprays. This is
because HFO contains high viscosity, a complex molecular structure which affects the
combustion process, presence of liquid phase soot, and variable fuel density. The injection
duration of a marine diesel engine ranges from 5 ms to 30 ms. HFO has high viscosity, and pre-
heating is required before it can be properly consumed by the engine. HFO consists of a wide
range of fuel components with large variation in molecular weight. This multicomponent fuel
behaves differently during combustion compared with fuel of narrow range molecular weight.
The lighter components will burn first followed by the heavier ones. As a result, the viscosity and density of the liquid fuel increases as the lighter components evaporate away.

This means that not only is the fuel viscous and heavier, but the viscosity and fuel density is changing continuously during combustion. Consequently, it is important to take into account the viscosity and density of the fuel in the spray atomisation process and consider how this affects the spray dynamics. The droplet breakup process needs to be investigated under such conditions. There is evidence of the presence of carbonaceous residue that forms liquid phase soot during the combustion process and this soot is different from soot that forms in the vapour phase. This means that the droplets may not completely evaporate and that the spray remains as a multiphase flow through most of the combustion process. Due to the formation of carbonaceous residue, the viscosity of the spray droplets is likely to remain high even at high temperatures. In the present study, a mixture of Canola oil and diesel fuel is used to produce a high viscosity fuel in the context of the non-evaporating spray studies.

1.2 Methodology

This project utilised both numerical methods and experimental methods. The numerical software package called "Star-CD v3.26" was used for the numerical simulation part of the project. Some numerical sub-models were modified and new sub-models were added to the Star-CD software to improve the simulation accuracy. Experiments were conducted using a custom-built High Pressure Spray Chamber (HPSC). The experimental results provided verification of the simulation results. The current work is applicable to any fuel (including biodiesel and ethanol) that may be used in an internal-combustion engine, as well as water sprays that are used to control NOx emissions.

The detailed process of a diesel spray starts from the beginning of an injection. Fuel is injected into the combustion chamber via a high pressure jet nozzle that opens for a duration of 5 ms for a medium speed marine diesel engine; up to 30 ms for a low speed marine diesel engine and approximately 1 ms for high speed diesel. The fuel expelled from the injector forms a jet with a plume of clouds of droplets in the frontal part of the jet. The jet initially penetrates the surroundings very rapidly and the jet is narrow and long. Within less than 1 ms after the start of injection, the jet begins to expand volumetrically and penetrates at a slower rate. As the volume of the spray expands, the penetration rate reduces. Such a rapid and instantaneous process of high energy droplet disintegration, formation of jet vortices and mixing of fuel and air, shows the complexity of the process.
Throughout the project the following assumptions are used:

1. The spray is injected at room temperature, with similar gas density to that of a diesel engine combustion chamber.
2. Chemical reactions are not taken into consideration.
3. Evaporation and other means of mass transfer from fuel to air are assumed to be negligible.
4. The spray is assumed to be injected into perfectly still air without additional turbulence.
5. The effects of boundary flow from the wall of the chamber have minimal effect on the spray dynamics and spray structure because the surrounding air flow is very low (less than 1 m/s) compared with the velocity of the jet (over 200 m/s).

1.3 Thesis Structure

The format of this thesis begins with a literature review of diesel spray dynamics. The fundamental process of diesel spray in general and the dynamics of droplets in jet spray are covered in the literature review chapter.

Chapter 3, entitled “Evaluation of Diesel Spray Simulation Models”, evaluates the different Lagrangian multiphase models. The Lagrangian (droplet phase) models were evaluated individually to better understand the model’s properties under typical diesel spray conditions. In each evaluation, the models were isolated so that only the effects from the model of interest were shown in the results without unwanted influence of other models. The theoretical accuracy of the model and experiment data validation from existing literature was used to quantify the ability to replicate the physics of a diesel spray using the numerical model.

Chapter 4, entitled “Experimental Studies of Diesel Spray”, describes the experiments conducted using a custom-built High Pressure Spray Chamber (HPSC) from the National Centre for Maritime Engineering and Hydrodynamics (NCMEH) at the Australian Maritime College (AMC), University of Tasmania (UTAS). The chamber was specifically designed to study long duration sprays of high viscosity fuel. A constant volume chamber was chosen instead of a piston crankshaft system (like in a real engine) because the chamber permits clear observation of the spray with a large window area, and viewing from various different directions is easily achieved. The chamber also allows the spray to be injected into still air without the influence of
external turbulent air flow prior to the start of fuel injection. Instrumentation was supplied by
LaVision and included a dual-frame CCD camera with lenses, a double-pulse 120 mJ laser with
light sheet optics, a high-efficiency diffuser, a long-distance microscope and an acquisition
computer. The experiment was broken into three parts, namely: spray penetration and cone
angle; light sheet Particle Image Velocimetry (PIV); and dropsize shadowgraphy using a long-
distance microscope. These three experiments allowed the acquisition of the macrostructure of
the spray, the velocity profile in the sparse region of the spray and the dropsize in the sparse
region of the spray.

Chapter 5, entitled “Large Eddy Simulation (LES) of Diesel Spray”, focuses on the full
simulation of diesel spray using LES. The LES was validated with experimental data.

The final main body chapter, entitled “Detailed Analysis of a Medium to Long Diesel Spray”,
is a qualitative studies of the diesel spray dynamics. The internal details of the spray structure
and the influence of the gas density and fuel viscosity on the spray structure is shown here.

Finally, the conclusions of the project and recommendations for future work are presented in the
final chapter.