

---

# Contents

---

|  |             |
|--|-------------|
| <b>Contents</b>  | <b>i</b>    |
| <b>List of Figures</b>                                     | <b>v</b>    |
| <b>List of Tables</b>                                      | <b>xiii</b> |
| <b>Nomenclature</b>  | <b>xv</b>   |
| <b>1 Introduction</b>                                      | <b>1</b>    |
| 1.1 General context . . . . .                              | 1           |
| 1.2 Objectives and methodology . . . . .                   | 2           |
| 1.3 Thesis outline . . . . .                               | 4           |
| <b>2 Technical background</b>                              | <b>7</b>    |
| 2.1 Introduction . . . . .                                 | 7           |
| 2.2 Aircraft engine operation . . . . .                    | 8           |
| 2.2.1 Combustor types . . . . .                            | 10          |
| 2.3 Fuel injection . . . . .                               | 11          |
| 2.3.1 Injectors for aircraft engine applications . . . . . | 12          |
| 2.4 Combustion regimes . . . . .                           | 16          |
| 2.5 Combustion technologies . . . . .                      | 17          |
| 2.5.1 Lean premixed prevaporized (LPP) . . . . .           | 18          |
| 2.5.2 Rich-burn, quick-quench, lean-burn (RQL) . . . . .   | 19          |
| 2.5.3 Lean-Direct Injection (LDI) . . . . .                | 21          |
| 2.5.4 Multi-point Lean-Direct Injection (MPLDI) . . . . .  | 22          |
| 2.5.5 Review of performance characteristics . . . . .      | 25          |
| 2.6 Summary . . . . .                                      | 25          |
| References . . . . .                                       | 27          |

|  |           |
|--|-----------|
| <b>3 Fund. of atomization, combustion and soot formation</b>   | <b>29</b> |
| 3.1 Introduction . . . . .                                     | 29        |
| 3.2 Atomization process . . . . .                              | 31        |
| 3.2.1 Useful non-dimensional numbers . . . . .                 | 31        |
| 3.2.2 Primary atomization . . . . .                            | 32        |
| 3.2.3 Secondary atomization . . . . .                          | 38        |
| 3.3 Representation of droplet . . . . .                        | 41        |
| 3.3.1 Mean diameter . . . . .                                  | 41        |
| 3.3.2 Mathematical distributions . . . . .                     | 42        |
| 3.4 Evaporation process . . . . .                              | 43        |
| 3.4.1 Drag forces . . . . .                                    | 44        |
| 3.4.2 Evaporation models . . . . .                             | 45        |
| 3.4.3 Spray-turbulence interactions . . . . .                  | 48        |
| 3.5 Turbulence-gaseous flame interactions . . . . .            | 49        |
| 3.6 Spray combustion . . . . .                                 | 52        |
| 3.6.1 Combustion regime . . . . .                              | 53        |
| 3.7 Soot formation . . . . .                                   | 55        |
| 3.7.1 Gaseous soot precursors formation . . . . .              | 57        |
| 3.7.2 Physical phenomena . . . . .                             | 57        |
| 3.7.3 Chemical phenomena . . . . .                             | 59        |
| 3.8 Summary . . . . .  | 59        |
| References . . . . .   | 60        |
| <b>4 Review of exp. configurations and spray burner design</b> | <b>69</b> |
| 4.1 Introduction . . . . .                                     | 69        |
| 4.2 Spray jet flame experimental configurations . . . . .      | 71        |
| 4.2.1 Unconfined burners . . . . .                             | 71        |
| 4.2.2 Confined burners . . . . .                               | 76        |
| 4.3 Spray burner design . . . . .                              | 80        |
| 4.3.1 Injection system . . . . .                               | 86        |
| 4.3.2 High-flow and high-temperature facility . . . . .        | 87        |
| 4.4 Summary . . . . .  | 88        |
| References . . . . .   | 89        |
| <b>5 Experimental tools and methodologies</b>                  | <b>93</b> |
| 5.1 Introduction . . . . .                                     | 93        |
| 5.2 Fuel atomizer . . . . .                                    | 93        |
| 5.2.1 Simplex pressure-swirl atomizer . . . . .                | 94        |
| 5.2.2 Injector orifice . . . . .                               | 95        |
| 5.3 Annular spray burner . . . . .                             | 98        |

|          |  |            |
|----------|--|------------|
| 5.4      | Measured parameters through optical techniques . . . . . | 98         |
| 5.4.1    | Velocity fields . . . . .                                | 99         |
| 5.4.2    | Droplet size and droplet velocity . . . . .              | 101        |
| 5.4.3    | Image processing . . . . .                               | 104        |
| 5.4.4    | Soot formation . . . . .                                 | 108        |
| 5.4.5    | Flame lift-off height . . . . .                          | 113        |
| 5.4.6    | Simultaneous optical setup . . . . .                     | 117        |
| 5.5      | Summary . . . . .  | 118        |
|          | References . . . . .                                     | 119        |
| <b>6</b> | <b>Experimental study of the atomization process</b>     | <b>123</b> |
| 6.1      | Introduction . . . . .                                   | 123        |
| 6.2      | Velocity fields . . . . .                                | 124        |
| 6.2.1    | Results . . . . .  | 125        |
| 6.3      | Droplet size and droplet velocity . . . . .              | 129        |
| 6.3.1    | General considerations . . . . .                         | 131        |
| 6.3.2    | Results . . . . .  | 137        |
| 6.3.3    | Comparison between measured and calculated SMD . .       | 146        |
| 6.4      | Summary and conclusions . . . . .                        | 148        |
| 6.A      | Appendix: velocity of the liquid film . . . . .          | 150        |
|          | References . . . . .                                     | 151        |
| <b>7</b> | <b>Spray combustion</b>                                  | <b>155</b> |
| 7.1      | Introduction . . . . .                                   | 155        |
| 7.2      | Lift-off height . . . . .                                | 155        |
| 7.2.1    | Results . . . . .  | 156        |
| 7.2.2    | Experimental correlation . . . . .                       | 162        |
| 7.3      | Flame propagation speed . . . . .                        | 165        |
| 7.3.1    | Droplet evaporation . . . . .                            | 166        |
| 7.3.2    | Flame propagation speed . . . . .                        | 166        |
| 7.4      | Soot measurements through diffused back-illumination . . | 172        |
| 7.4.1    | Results . . . . .  | 172        |
| 7.5      | Summary and conclusions . . . . .                        | 180        |
| 7.A      | Appendix: droplet evaporation . . . . .                  | 183        |
|          | References . . . . .                                     | 184        |
| <b>8</b> | <b>Summary and future works</b>                          | <b>189</b> |
| 8.1      | Summary . . . . .  | 189        |
| 8.2      | Future directions . . . . .                              | 192        |
|          | <b>Global Bibliography</b>                               | <b>195</b> |