Example

Instructions to complete the form: As part of a successful graduate thesis defence you must demonstrate that your thesis meets or exceeds the expectations concerning your performance and personal development associated with a set of attributes that are listed in the first column of the table below. The second column lists the expectations for each attribute. In the third column you should write one or more bullet points to clearly demonstrate, by providing evidence, how you have met (or exceeded) those expectations. An example is given below in order to indicate how you might complete the form for your own research.

Student Name:___ ____ **Supervisor/co-supervisor:____**

Thesis Title: _Experimental investigation of the turbulent flow structure in a heated square tube and its influence on the convective heat transfer

	Graduate Thesis Expectations	Thesis Self-Assessment
Depth and breadth of knowledge	• Good understanding of the knowledge base related to the area of research	• I took two graduate course related to the field of research, which are "Convection Heat Transfer" and "Mechanism and Theory of Turbulent Flows". These courses enhanced and broadened the fundamental knowledge related to convection heat transfer and turbulent flows which are the two fields directly related to the thesis topic. • The other two courses I took were "Experimental Measurements in Fluid Mechanics" and "Applied Measurement and Sensing Systems". Both of these courses enhanced and broadened my knowledge related to experimentation and measurements, specifically the measurement techniques I used in my research. • My knowledge base was further improved by reading standard textbooks including Fundamentals of Heat Transfer by Incropera and Turbulent Flows by Pope.
	• Good understanding of the broader scope of the research problem and how the current research fits into the big picture is demonstrated	• The specific focus of the research is on the investigation of turbulent flow structure in a square tube heated through the bottom wall, which is expected to contribute to the design improvement of heat sinks through active cooling. The broader application of this research is the improved cooling of electronic equipment, especially the high-power computing devices in data centres. • These aspects are described in detail in the Introduction and motivation sections of Chapter 1 in the thesis.

	• Good knowledge of one or more specialized techniques (Analytical, numerical or experimental) in the area of research	• The thesis research was experimental in nature. The state-of-the-art Particle Image Velocimetry (PIV) technique was used to measure the flow velocity fields in two-dimensional planes with vertical and horizontal orientations. • I have learned the PIV technique and implemented it in my experiments. • The standard software for the PIV data processing was used. However, I modified in-house computer codes for the post processing of the PIV dataset.
Research & scholarship (General)	• Detailed review of the relevant scientific literature	• Reviewed over 50 papers focused on turbulent flows in circular and square tubes. • Reviewed about 30 papers that investigated heat transfer from heated tube walls including isothermal walls, bottom heated walls and differentially heated walls. • Reviewed around 20 papers that studied the relative influence of forced and free convection in circular and square tubes over a range of Reynolds numbers. • These reviews are summarized in Chapter 2 of the thesis.
	• Synthesis of recent advancements in the field of research	• While numerous scientific studies have been conducted in this field of research there is no general consensus on two key fundamental points, (i) the distance from the heated wall over which which the buoyancy effects are significant in enhancing heat transfer, and (ii) how the buoyancy-driven flow influences the structures of the turbulent flow in the tube. • Previously, the turbulent behaviour of the flow was mainly characterized through the magnitude of turbulent intensities, but the roles of Reynolds stresses and the production and dissipation rates of turbulent kinetic energy have not been well documented in the published scientific literature. • In addition, the heat transfer behaviour was mainly characterized through the bulk Nusselt number and, hence, the knowledge of the variations in the local Nusselt number, in particular near the heated wall, is currently limited.
	• Adaptation of a logical approach to address research objectives	• The primary research objectives in this thesis work are (i) to characterize the turbulent flow structure in a square tube subjected to bottom heating and (ii) to investigate the influence of flow structure on the convective heat transfer. Two approaches are used to address these objectives. • In the first approach, velocity fields were measured at different operating conditions in the vertical mid-plane of the tube and multiple horizontal planes at different distances from the heated wall to accurately capture the three-dimensional flow behaviour. The operating

		conditions varied from a Reynolds number of 4,000 to 10,000 and the bottom wall temperature varied from 40^{o}C to 70^{o}C, which corresponded to the variations in the relative contributions of inertial and buoyant forces. • In the second approach, the temperature field within the flow domain was measured using an array of thermocouples at the same locations as for the velocity measurements. Due to the limitation of the PIV technique, both velocity and temperature measurements could not be performed simultaneously. The temperature measurement allowed characterization of the buoyant forces as well as the local heat transfer.
	• Presentation of research results in a systematic manner within the context of the given objectives	• The results are presented in a systematic way within the context of the research objectives. In Chapter 4, detailed velocity results, including the profiles of mean and turbulent velocities, turbulent shear stress and energy production and dissipation rates, are presented and discussed for each operating condition. The turbulent vortices are also detected and their properties investigated. • In Chapter 5, the temperature results for the same conditions are presented and discussed. Later in the same chapter, the velocity and temperature results are discussed collectively to provide a coherent description of the underlying physical processes governing the interaction of buoyancy-driven and inertia-driven flows and their influence on the turbulent flow structure and heat transfer rate. • Some key results are also presented in a form that allows their comparison with the results reported in the literature.
Research & scholarship (Critical thinking)	• Questioning of the viewpoints presented in the scientific literature	• It has been argued in the literature that the bulk Nusselt number is a reasonable parameter for characterizing the convection heat transfer. However, the vortices produced by turbulence play a dominant role in the transport of heat. Hence, these vortices control the local magnitudes of the heat transfer rate and, thus, for accurate characterization of the convective heat transfer, the influence of local vortices needs to be properly accounted for. • Previous studies suggested that the mean velocity profile should be symmetric about the tube centreline. However, the heating from one wall would create temperature non-uniformity in the fluid, altering the fluid viscosity, which would influence the local fluid velocity and, hence, the structure of the mean velocity field.

	• Clear description of the critical issue(s)/problem(s) addressed by the thesis research	• The critical issues addressed by this thesis research are (i) the influence of buoyancy on the turbulent flow structure, (ii) the role of turbulent vortices in controlling the local heat transfer rate and (iii) the effect of operating conditions on the interaction of buoyancy-driven and inertia-driven flows.
	• Logically tying of conclusions to the thesis objectives; adapted approach and related outcomes	• The first main conclusion of the thesis is that the buoyancy influences the turbulent flow structure when the wall temperature is high and the flow rate is low i.e. when the Grashof to Reynolds number ratio is close to unity. This conclusion addresses the first and third objectives of the thesis. • The second main conclusion is that the turbulent vortices are stronger near the heated wall and become weaker and fewer as the distance from the heated wall increases and, hence, the heat transfer rate is faster near the heated wall. This conclusion addresses the second objective.
Application of knowledge	• Accurate and systematic application of existing knowledge to analyze the research problem	• The knowledge gained by the thorough review of previous studies on the flow in a rectangular tube was utilized to design and built the experimental apparatus. • The knowledge of the PIV technique was also considered to ensure its accurate implementation in the experiments. • The methodologies adapted in previous studies to analyze the velocity and temperature fields were used in the current research. It includes equations and correlations to compute various turbulent characteristics and dimensional and non-dimensional heat transfer parameters.
Professional capacity / autonomy	• Demonstration of academic integrity and research ethics	• The research work was primarily conducted by me. There was some involvement of two members of the research team in the experimental setup and measurements. In addition, there was one industrial collaborator involved in the research work. The share of each contributor is clearly described on page XX in the thesis. • The results and conclusions from previous studies used in the thesis are properly cited and referenced.
Communication skills	• Thesis form and layout is consistent with the SGPS format	• Thesis has the monograph format, which complies with SGPS specifications.
	• Thesis is free from typographical and grammatical errors	• Thesis has been thoroughly reviewed (including by <name, position/title> and <name, position/title>) and corrected for any typographical and grammatical errors. • Additional help was also received from the Writing Support Centre at Western to improve

		writing skills.
Awareness of limits of knowledge	• Awareness of the complexity of scientific problem under consideration and limitations of existing tools and techniques to address it is acknowledged and their consequences on the research outcomes are properly discussed	• The flow field considered in this study is three-dimensional in nature. The PIV technique used in this study can measure two-components of velocity in a two-dimensional plane. Hence, measurements in vertical and horizontal planes were conducted to capture the three-dimensional effects as best as possible. However, no measurements were conducted in the pipe cross-plane due to experimental limitations. Hence, the three-dimensional flow structure was not fully captured. • The experimental limitations in the current work are discussed and acknowledged in Chapter 3 (Experimental Setup). • The limitations of the experimental tools and approaches used and their consequences on the research outcomes are clearly acknowledged in Chapter 4 where the turbulent flow characteristics are described, as well as in Chapter 5 where the interaction between inertia-driven and buoyancy-driven flows is discussed.
	• Consequences of the assumptions considered in the research work and the uncertainty induced in the results due to the limitations of the research tools are clearly described	• The uncertainties in the results came from the uncertainties in the PIV velocity computation, electric heater controller, and thermocouple and flow meter measurements. These uncertainties are documented in Chapter 2 and, where appropriate, presented in the results in the form of error bars. • For the experimental apparatus, it was assumed that (i) the tracer particles used for PIV measurements are neutrally buoyant and (ii) the flow was hydrodynamically and thermally developed at the measurement location. • For the data analysis, it was assumed that (i) the heat loss from the side walls is negligible and (ii) the magnitude of the span-wise velocity component is negligible compared to the streamwise and vertical velocity components. Furthermore, the thermophysical properties were computed at the average fluid temperature. • The consequences of these assumptions are discussed in Chapters 3, 4, and 5.

Additional comments: ____

Student's signature: ____

Date: ____