

# Diploma Thesis Review

Mass Flow Estimation and Control in Pump Driven Hydronic Systems

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This thesis investigates the estimation and control of mass flow in hydronic systems. This topic, of significant practical relevance, is well motivated in Chapter 1, where the potential for energy savings by replacement of commonly used throttling valves with small pumps is discussed. This reviewer is of the opinion that the inevitable trade-off between potential for energy savings and solution cost (associated with the use of small pumps) could be mentioned as a potential limiting factor in deployment of such solutions. Chapter 1 continues with the author motivating the use of Kalman Filtering for estimation of mass flow, and also the need for a physically representative hydronic system model. After introducing the applied control design techniques, a brief organization of the thesis is given. The problem statement is well motivated, a set of objectives are clearly defined, and a sound engineering methodology is presented in order to meet the aforementioned objectives.

The thesis is built upon 7 subsequent chapters, with a total of 24 references cited from the literature and running to a total of 72 pages including appendices. Chapter 2 defines data fusion, and attempts to classify data fusion methods and techniques. Identifying that the mass flow estimation problem at hand is a state estimation problem, an overview of commonly used techniques is given, leading to an introduction of Kalman Filtering for discrete, linear systems and finishing with the Extended Kalman Filtering for discrete non-linear systems, which is the technique predominantly used in this work. Chapter 3 introduces the underlying hydronic system model and discusses modelling techniques, leveraging the electronic-hydraulic analogy. A single non-linear differential equation is derived, governing the fluid flow in a hydronic system. Chapter 4 introduces the experimental test bench. The crucial power-flow characteristic is identified from experimental data and an excellent discussion on the statistical assumptions associated with voltage and current measurements is presented, in preparation for the Extended Kalman Filter design. An existing hydronic system model was enhanced to include the previously calibrated power characteristic. Chapter 5 briefly describes the implementation of the Kalman Filter, including the existing software tools that were used, and an important discussion numerically robust implementations of the Extended Kalman filter using a modified Cholesky factorization. Chapter 6 builds upon the previously designed mass flow estimator and proposes two control design strategies of varying complexity, namely a PI controller and an LQR type controller, based on Jacobian linearization combined with feedforward. Chapter 7 presents simulation based validation of the previously designed mass flow estimation techniques and both control strategies. Chapter 8 presents conclusions. A detailed derivation of the model used in the Extended Kalman Filter design is left to Appendix B, including discretization techniques, state augmentation for joint parameter and state estimation and derivation of the relevant Jacobians. Overall, the thesis is well structured and the objectives outlined in the introduction have been fulfilled to a satisfactory level, notwithstanding the the lack of available test-bench for experimental validation. Despite being excellently worded with excellent English, minimal misspellings or grammatical mistakes, it would have been preferred had the thesis been written in the passive voice, rather than first person. The author demonstrates a solid command of the modelling, estimation, control design and data analysis techniques used, however the bibliography is rather sparsely populated. Chapter 2 and Chapter 3 would both benefit from a more deep discussion of existing works in the literature, both new and old. Furthermore, it would have been beneficial, especially considering that the topic under analysis is of such practical relevance, to provide some references, if any exist, particularly in relation to mass flow estimation for hydronic networks.

Despite this work being completed to a high-level in general, there are a few aspects that do leave some scope for improvement. In Chapter 2.4.2, there is a slight inconsistency in the notation with respect to the measurement function  $h$  as defined in the equations governing the process and state measurement update equation  $\hat{x}_k$ . In Chapter 3.2, the pipe model is introduced and it is stated that  $\Delta p_R = Rq^2$  where  $\Delta p_R$  is the pressure difference across the resistance,  $q$  is the mass flow and  $R$  is the hydraulic resistance. This, is a crucial model component and could well do with a better exposition. Furthermore, how about the functional dependence of  $R$  on, for example Reynold's Number? **In a similar vein, in Appendix B, B.23 assumes that the hydraulic resistance is constant parameter. Could you justify this assumption?** In Chapter 4, a schematic of the hydronic system would be appreciated, together with a picture of the experimental test-bench. In Chapter 5.3.1, does implementation of the modified Cholesky factorization have any other impact on e.g. computational performance of the algorithm? This can be important for deployment of any such solution where hardware constraints are present. In Chapter 6.2.4, Figure 6.3 has inconsistent notation on axes particular with respect to Revolutions. Furthermore, it would be of benefit to explain in more detail how the gain scheduling is implemented. In Chapter 7, the results of the mass flow estimation are well presented and provide convincing arguments for the efficacy of the proposed estimator. It may help visualize the results by overlaying the estimated standard deviation of mass flow on the estimated mass flow chart itself. Furthermore, in 8.2 a qualitative control comparison could be helpful, using e.g. Integral of Absolute Error. Although it is deduced that the due to the complexity of the LQR based, the PI controller is preferred as it has comparable performance, **could the author conceive any setup or topology where the use of the LQR controller may be required?** It may be useful to briefly discuss these pros and cons.

### Conclusions

Overall, my comments outlined above do not recommend any major changes. It is indeed unfortunate that experimental validation was not possible due to test-bench limitations. This however does not negatively impact on achieving the objectives that were outlined at the beginning of this thesis, which were all completed and discussed in detail. I recommend that this diploma thesis be presented for defense and that the mark of **B-very good** is awarded.