Stratification in storage tanks for heat pump

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Introduction

This research investigates the behavior of thermal energy storage (TES) experimentally and with the help of simulation. The point of focus throughout this thesis is the thermal stratification assessment carried using pre-established indices found in the literature, using own custom built second law model and also using CFD code. The three specific objectives of this thesis are:

- Design and simulate the methodology to separate the good from the bad operational parameters during TES operation from the view of stratification quality and thus efficiency of renewable heat sources connected to TES.
- Design and validate own custom built second law model to quantify the availability of the energy that is being added and subsequently removed during charge and discharge cycle of TES.
- Design and build an intelligent IoT stream processing unit to fit the second law model previously developed and predict the second law stratification efficiency in real time.

A novel modelling approach to evaluate the stratification efficiency in storage tanks for heat pump was developed. Custom built models, in addition to custom built IoT stream processing system allowed for effective evaluation of stratification efficiency of TES in real time mode.

This methodology reflects the limitations of old approaches which are based on first law of thermodynamics. These limitations were addressed in 'research gap' and were subsequently enriched. Advanced second law models were developed as a part of this enrichment. Furthermore, a 'performance gap' of previous first law approach was identified. This performance gap was enriched by customizing a novel IoT stream processing device. Enrichment of both research as well as performance gap worked in union to evaluate effectively and automatically the full charge and discharge cycle of TES integrated with heat pump.

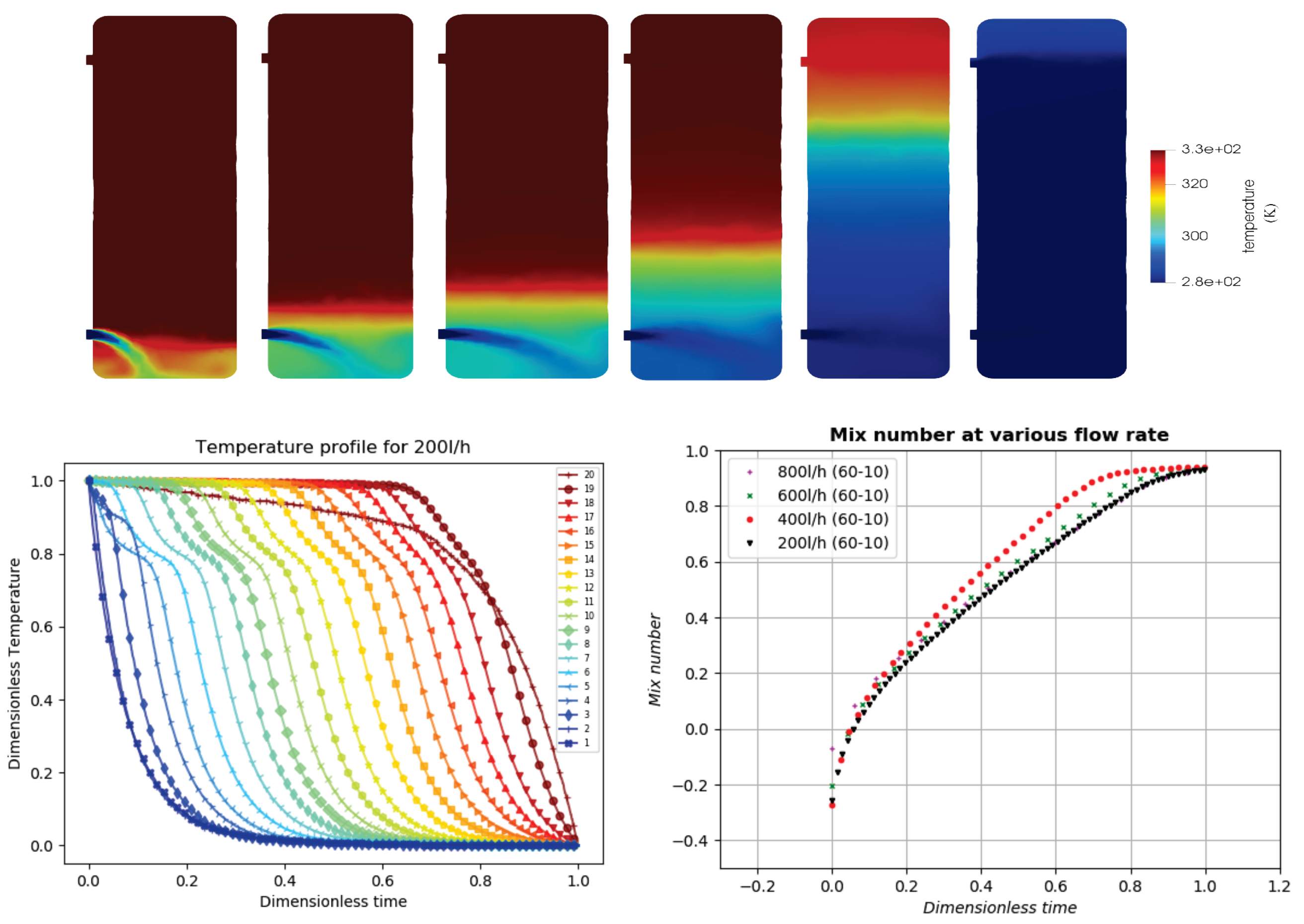


Fig. 1 CFD modelling of TES to understand limitations of first law models

STEP	WORK-FLOW OF THE DEVELOPED MODELLING METHOD
1	**CFD modelling to understand the limitations of first law models:** • First law models were calculated by the data collected from CFD models • These models were analyzed for different TES parameters and inlet design • Research gap identified
2	**Development of novel second law models as per research gap finding:** • Availability, exergy and entropy generation in TES were calculated using second law models. This provided improved insight in TES stratification process in contrast to first law modelling approach • The validated second law models were applied for different TES and heat pump parameters in the experiments
3	**Development of custom IoT stream processing edge device:** • A streaming data layer edge device was developed which analyzed the stratification efficiency using improved second law models in the previous step • Automated analysis of full charge and discharge cycle was performed, giving more insight into energy disbursement from electric grid to load
4	**Neural network modelling to predict the stratification efficiency:** • Stratification efficiency thus calculated quantitatively was predicted using data driven approach of neural networks • This also served as validation of quantitative approach in addition to the application of data driven approach in predicting the stratification efficiency in TES

Methodology:

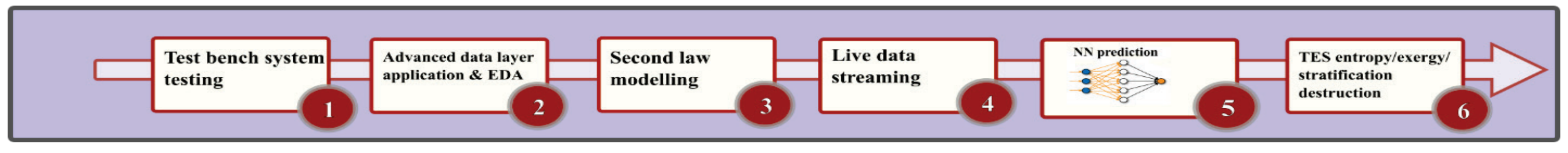
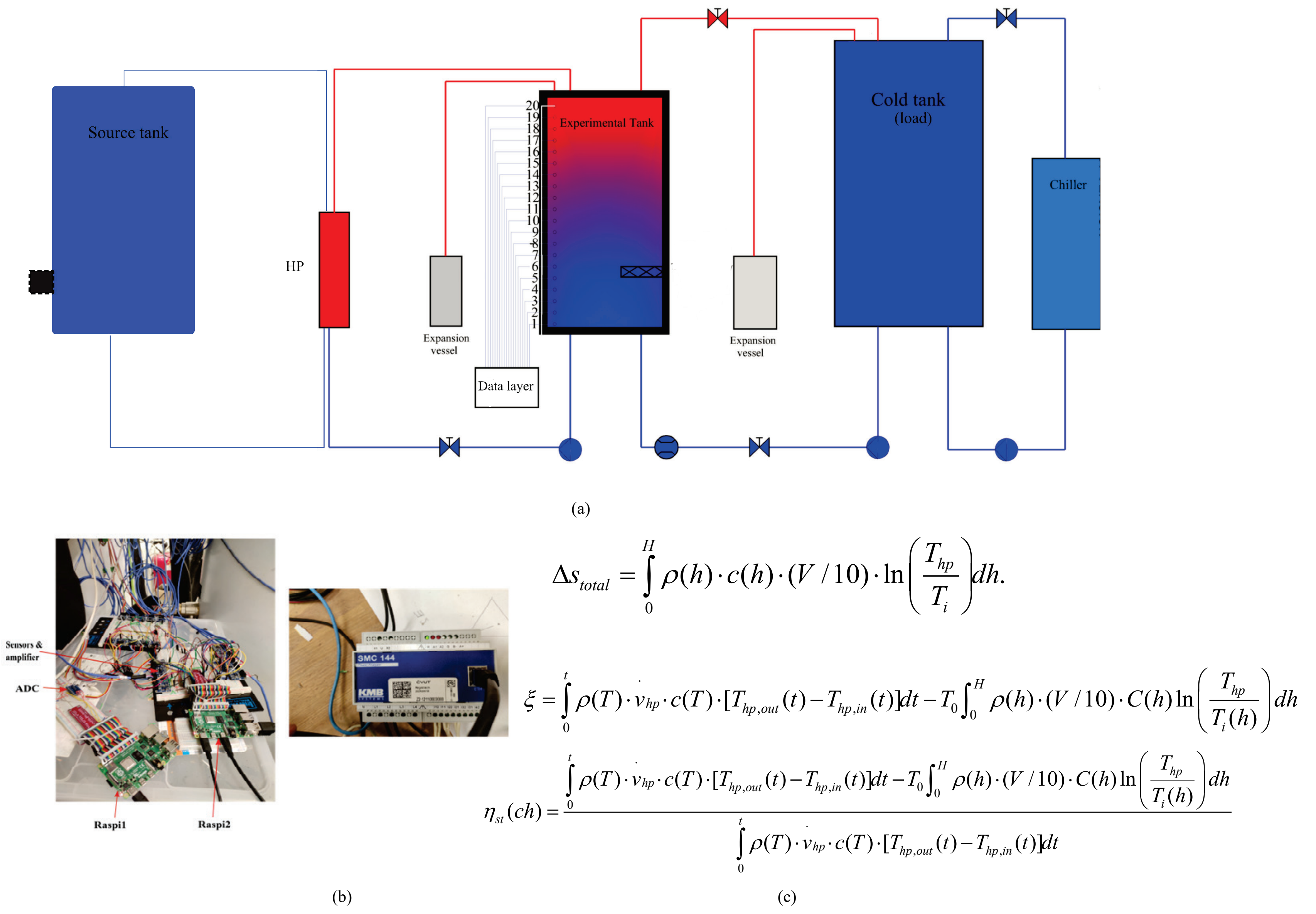

Test bench system testing ①
Advanced data layer application & EDA ②
Second law modelling ③
Live data streaming ④
NN prediction ⑤
TES entropy/exergy/stratification destruction ⑥

Fig. 1 shows the CFD model. First law models for various input parameters of TES were evaluated. Limitations of these models were identified. Second law models were developed as an improvement. These models allowed to calculate end to end energy expenses of the whole system. First equation in Fig.2 (c) is entropy change, second is the exergy, while third is the stratification efficiency of TES. Fig. 2 (a) describes the schema of experimental setup to collect the data. Fig. 2 (b) is the data layer. The sooner the data layer collects the data from experimental setup, it dynamically plots the temperature profile of TES and heat pump parameters, see Fig. 3 (a) & (b). Heat pump parameters include heat capacity, electricity consumption, and COP of the heat pump. Fig. 3 (b) shows the work of the developed second law models. Entropy and exergy generation in the TES at different compressor speeds were calculated during charge and discharge cycles. Fig. 4 (a) & (b) shows NN architecture. Fig, 4 (c) & (d) shows the prediction against calculated stratification efficiency. The NN reproduced results calculated by the quantitative models. Thus data driven approach validates the quantitative approach.



$$\Delta s_{total} = \int_0^H \rho(h)\cdot c(h)\cdot(V/10)\cdot\ln\left(\frac{T_{hp}}{T_i}\right)dh.$$

$$\xi = \int_0^t \rho(T)\cdot\dot{v}_{hp}\cdot c(T)\cdot[T_{hp,out}(t)-T_{hp,in}(t)]dt - T_0\int_0^H \rho(h)\cdot(V/10)\cdot C(h)\ln\left(\frac{T_{hp}}{T_i(h)}\right)dh$$

$$\eta_{st}(ch) = \frac{\int_0^t \rho(T)\cdot\dot{v}_{hp}\cdot c(T)\cdot[T_{hp,out}(t)-T_{hp,in}(t)]dt - T_0\int_0^H \rho(h)\cdot(V/10)\cdot C(h)\ln\left(\frac{T_{hp}}{T_i(h)}\right)dh}{\int_0^t \rho(T)\cdot\dot{v}_{hp}\cdot c(T)\cdot[T_{hp,out}(t)-T_{hp,in}(t)]dt}$$

(c)

Fig. 2 (a) Experimental schema, (b) data layer, (c) second law models

Results

Three distinct compressor speeds and tapping rates were studied using this data-streaming edge device and their exergy disbursement was studied in live mode. . Maximum entropy was generated at 800 l per hour – the highest flow rate. Minimum entropy was generated at lowest flow rate i.e. 400 l per hour. Furthermore, 25,000 kJ of entropy was generated at highest discharge rate while only 6000 kJ at highest charging rate. So, this can be concluded that discharging at lowest flow rate while charging at moderately higher flow rates makes the system more efficient thermodynamically.

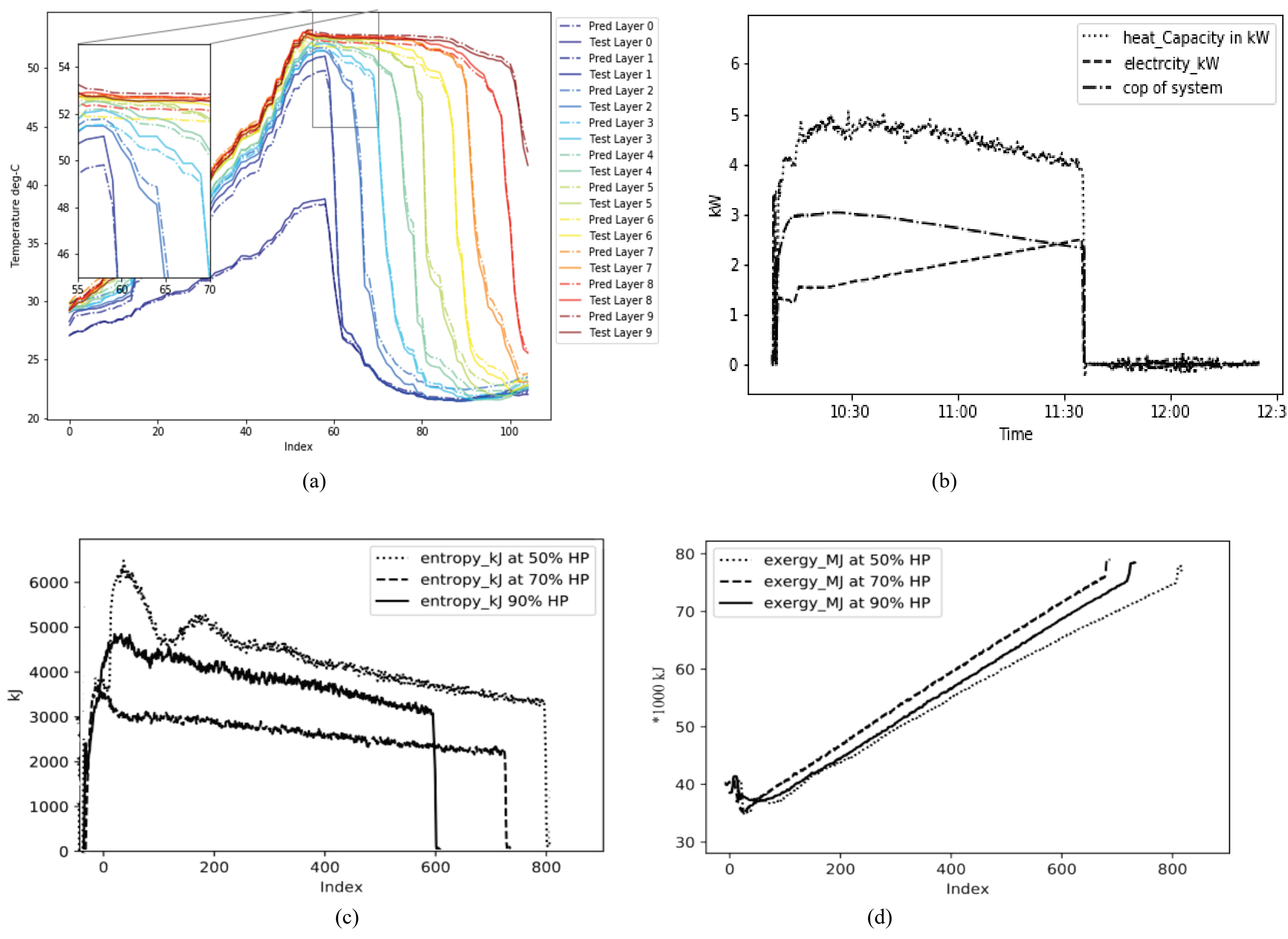


Fig. 3 (a) temperature profile (exp.) vs. prediction (neural network), (b) heat pump parameters, (c) entropy, and (d) exergy in TES

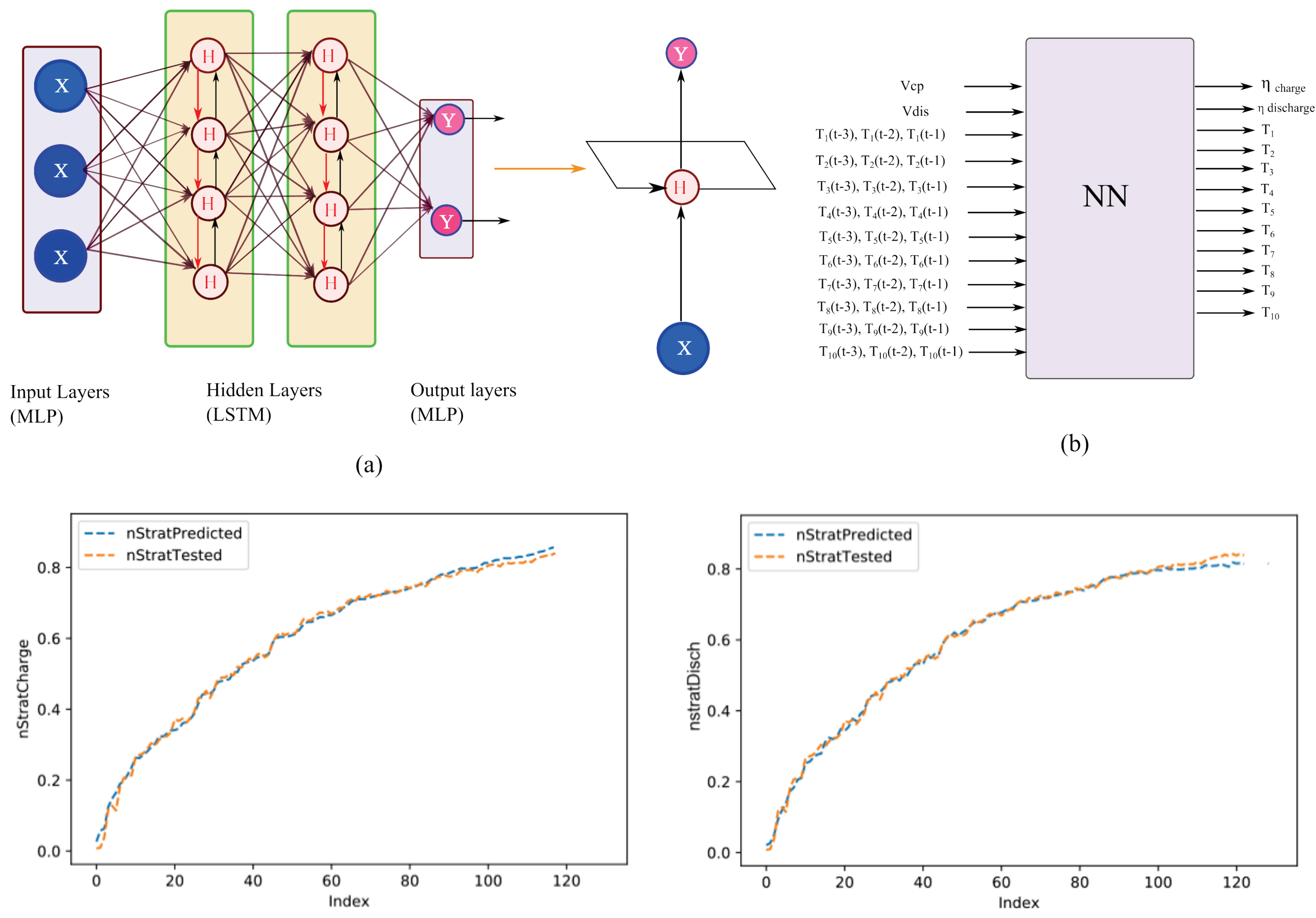


Fig. 4 (a) Architecture of used neural network (NN), (b) I/O parameters of NN, (c) stratification eff. during charge, and (d) stratification eff. during discharge in TES

Conclusion

CFD part of this research focuses on the influence of various inlet devices on stratification degradation. This involved first law of thermodynamics whose limitations were identified. As an improvement in methodology, the second law of thermodynamics was considered in developing models for entropy and exergy. These models along with the custom built stream processing edge devices allow for real-time monitoring of TES performance and heat pump efficiency during charge/discharge cycles. Advanced deep learning algorithms specifically LSTM neural networks were used to model the data collected by edge device and to predict the TES layered temperature and efficiency. The neural network prediction is considered as data driven approach to evaluate the stratification. And it is also used to validate the quantitative models developed. The error between quantitative and predicted results lied within 5% range. The exergy balance presented in the thesis measures the effective utility of the heat pump integrated with the TES system.

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