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Micro–Climate Control in a Grow–Cell: System Development and Overview

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Abstract: The research behind this article aims to reduce the operational costs and energy consumption of closed–environment growing systems, or grow–cells. Essentially a sealed building with a controlled environment, and insulated from outside lighting, grow–cells are configured to suit the particular crop being produced. There are numerous research questions relating to their design and operation, including their energy requirements, air movement, dehumidification, internal racking design, different ways to deploy artificial LED lighting, and the monitoring of crop reaction to these. The present article briefly reviews the concept and describes some preliminary work in relation to a demonstration system deing developed by the authors and collaborating industry partner. This prototype consists of a $12m \times 2.4m$ shipping container with a commercial heating/ventilation system. Multi–layer growing trays are circulated by means of a novel conveyor system. The article describes the development of the conveyor control system, summarises research into LED light selection, and introduces the thermal modelling approach. The latter is illustrated using experimental data from a laboratory scale test chamber.

Keywords: Modeling and Control of Agriculture; Plant Factories; Optimal Control in Agriculture; Distributed Control of Environmental Systems; Modeling and Identification

1. INTRODUCTION

The research behind this article aims to reduce the operational costs and energy consumption of closed–environment growing systems, or grow–cells. Essentially a sealed building with LED lighting and a controlled environment, grow–cells are configured to suit the particular crop being produced. When compared to greenhouses, the energy requirements, water consumption and carbon emissions are *potentially* lowered in an optimally designed system. Other conceptual benefits include crop growth in climatic conditions which previously were not suitable; crops are grown under sterile conditions, eliminating the need for pesticides; and grown closer to the final consumer, reducing transportation costs. There is also considerable scope for investigation of a range of biological and horticultural issues, for example crop delivery date and flavour, by on–line regulation of the lighting and micro-climatic systems. For these reasons, there is now considerable academic and industrial interest in the development of practical grow–cell systems [e.g. Foresight, 2011].

However, challenging research questions remain relating to their design and operation, including their energy requirements, air movement, dehumidification, internal racking design, different ways to deploy artificial lighting, including stationary or moving, and the monitoring of crop reaction to all these. Furthermore, numerous research problems are concerned with heating agricultural buildings in general, and for supplying nutrients to plants, hence a vast scientific literature exists describing models and controllers. Taking the problem of temperature regulation as a key exemplar, one recurring theme is that heat transfer has a complex and spatially heterogeneous nature [e.g. Price et al., 1999]. Typical causes of imperfect mixing include multiple flow regions, stagnant zones and short–circuiting to the exhaust outlet. There are broadly two types of model describing these dynamics: computational fluid dynamics and data–based (statistical) models: see Foucquier et al. [2013] for a recent review.

The desired climatic conditions may differ from zone to zone, hence the ultimate goal is to act on the heating and ventilation devices in such a way, that the design requirement for each zone is reached. Agbi et al. [2012], for example, applies data–based methods to multi–zone thermal systems in buildings. The present project also focuses on the data–based approach, since it generally leads to relatively straightforward, dominant mode models suitable for control system design.

In this context, past research at Lancaster University has developed a *true digital control* approach to control system design. Here, a data–based model identification and parameter estimation stage, is followed by non–minimal state space control system design and robustness evaluation, using a digital, sampled–data standpoint throughout [see e.g. Taylor et al., 2013, and the references therein]. The approach has already been shown to work well for micro–

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Fig. 1. Grow–cell unit.

climate variables within a lumped parameter setting [e.g. Lees et al., 1996, Taylor et al., 2004, Stables and Taylor, 2006]. However, the present research aims to utilise measurements from neighbouring zones as state variables, an approach that yields nonlinear state–dependent control algorithms [Taylor et al., 2011]. Similar methods have been recently applied in other discipline areas [Taylor and Robertson, 2013, Taylor and Aerts, 2013].

This article reviews the grow–cell concept (section 2) and describes preliminary work in relation to a demonstration unit deing developed by the authors and collaborating industry partner (Fig. 1). The prototype is based on a $12m \times 2.4m$ shipping container, with a refrigeration unit and heat exchanger. Multi–layer growing trays under LED lights are circulated by means of a novel conveyor system. Hence, the article also describes the conveyor control program and summarises research into LED light selection (section 3). Finally, the thermal modelling approach is briefly illustrated using experimental data from a laboratory scale test chamber (section 4).

2. BACKGROUND

Future food supply and optimization of agriculture was already a concern by the early 20th century. Ball [1921], for example, observed that 'smart' land manipulation by merging know–how from various scientific fields would compensate for the rapid increase of population and the lack of remaining lands suitable for cultivation. With regard to growing plants in controlled environments, an early citation is Davis and Hoagland [1928]. In more recent times, the central idea around future food production has not changed but the standards required are much more challenging [Foresight, 2011]. In this context, argued benefits that arise from developing artificial environment growth facilities include:

- *Flexibility to grow crops at any geographical location.* With compact facilities, thermally insulated, insulated from external lighting, and equipped with a Heating–Ventilation–Air–Conditioning (HVAC) system that is sized according to the crop type and local climatic conditions, grow–cells potentially permit any type of crop growth to take place.
- *Effective management of land usage.* Within a grow–cell, multiple tier configurations can be realised with respect to a plant's potential spatial occupation characteristics. Therefore, it is feasible to grow a required crop mass at a much smaller physical scale than would be possible using conventional methods.
- *Pricing of end–product and food waste management.* Transportation and storage costs, as well as temporal availability, all contribute to the final price of a crop. Moreover, its freshness and nutritional value is inevitably changed during transportation. Using grow–cells, local production can be encouraged, with reduced transportation related CO_2 emissions.

It is clear, however, that to help realise such benefits, there is a requirement for multidisciplinary research into various design, optimization and control issues. The underlying challenges when compared to conventional greenhouses are energy usage and optimised crop production. Both depend on a number of factors, including climate control performance, correct sizing of the air–conditioning unit depending on the geographical location, the influcence of LED light on crop growth and morphology manipulation, insulation of the building envelope, and so on. For instance, if a particular plant species optimal light recipes are defined through LED growth trials, it will be possible to accelerate and maximize vegetation and flowering processes. In order to investigate some of these issues, the present authors and partners have developed a pilot system, as discussed below.

3. DESIGN ASPECTS

The grow–cell concept is generally based on a modular system, in which multiple units can be aligned and stacked as the facility grows in size. However, the single–unit prototype considered in this article consists of a commercially available shipping container, initially using an in–built refrigeration unit for environmental regulation, i.e. with a heat exchanger, and industry standard temperature and humidity control system. A quarter of the unit has been partitioned off in order to facilitate monitoring, data acquisition, control equipment and power supplies. The remaining space is split into two $1.2m \times 9m$ components. One side is the growing space, in which the growing trays are circulated by means of a conveyor. Each layer of the conveyor is fitted with LED grow lights and single point irrigation. For initial research purposes, the other side is left empty to allow for easy access.

3.1 Conveyor System

The significance of spatial variability has always been an important issue for controlled environment growth facilities [van Bavel, 1979]. Since the eventual grow–cell product is intended to be fully occupied, there are potential benefits in moving the plants around the environment. This approach can partially compensate for the imperfect mixing alluded to above. Moreover, since it will be physically impossible for the end–user to walk inside the growing area of a commerical system, relocation of the plants at specified time intervals to allow for single point inspection and/or delivery of plants to the growing area entrance, will be an essential feature.

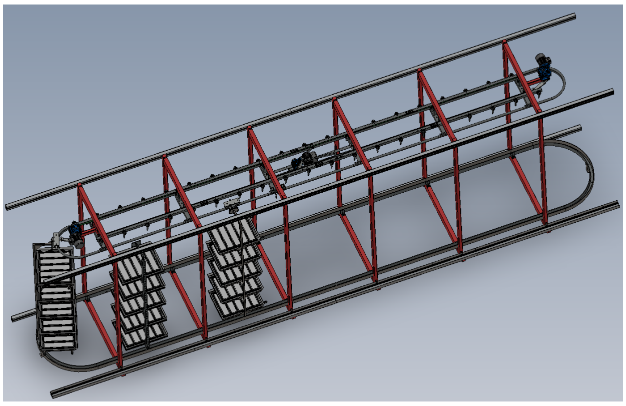

Fig. 2. Conveyor structure schematic.

The bespoke conveyor system for the pilot grow–cell is illustrated in Fig. 2. It employs three motors to actuate circulation of the tray hangers. The main motor, which is placed at the centre of the structure, is used for horizontal motion. In addition, a sweep motor is placed at each end of the structure. These 'sweep' the tray hangers when they arrive at the turn point, where the main motor has no mechanical effect. All three motors are of an asynchronous type, enclosed and equipped with fan–cooled ventilation. They have cage rotors made of aluminium and are fitted with 100:1 ratio worm gear units in order to simultaneously decrease operating speed and increase output torque.

The control process is based on 4 sensor signals, the combination of which enables the required horizontal or sweep motion. More specifically, two photoelectric sensors are placed at one end (turn point) of the structure. When one of these detects that a tray hanger is ready to be carried across and the other detects that there is space available to receive it, then the sweep transfer motion is activated. The reverse combination activates the main motor in order to bring the tray hangers into position for a new sweep. A proximity sensor detects 360° rotation of each sweep motor, in order to control its starting point. The central processing unit employed to carry out these operations is a 'smart relay' from Schneider Electric$^{\text{TM}}$(model: *SR3B261BD*).

The system has been programmed to operate in three modes, namely Automatic, Manual and Stand–by. The latter is provided in order to stall the system at any time. In Automatic mode, the operation is continuous and each full cycle occurs after a pre–set time delay. The delay timer can be modified using the control system panel, which is also used to inform the operator in real–time about the sensor status and active alarms, if present. In Manual mode, one full cycle occurs at the press of a button. Finally, an interlock switch is used to indicate whether the entrance to the conveyor area is blocked or not. If this switch is activated, the process is paused immediately to prevent potential injuries to human and/or equipment.

3.2 LED Lights

The most important factors that affect plant growth within a controlled environment are (i) the micro–climate conditions and (ii) the availability of useful light for photosynthesis. Until quite recently, light–emitting diode (LED) technology was not a commercially viable medium to use for providing plants with light, largely because of inadequate performance. However, their ability to emitt light at specific wavelengths has always intrigued researchers and, over the last few years, their efficiency has improved significantly, especially for emitting light at the green and blue wavelengths [Hahn et al., 2000, Lin et al., 2013]. As a result, LED grow lights are attracting increasing attention from stakeholders in the horticultural industry.

The spectral properties of LED lights depend on the properties of the raw materials used for their manufacture. Within the context of plant growth, this is particularly useful because plants make more efficient use of certain wavelengths within the visible spectrum region. For example, a spectral output of 620 to 680nm (red colour) has a particular influence on the photosynthetic process [Bula et al., 1991, Sager and McFarlane, 1997]. This suggests the possibility of merging a mixture of LED colours in one unit, so that it satisfies a plant's needs without wasting light energy at other wavelengths.

Another feature of LEDs is their long–lasting operational cycle [Barta et al., 1992, Bourget, 2008], which implies significant cost savings in the long term. Other useful characteristics include instant ON–OFF operation, their relatively small size and significantly lower heat output than other lighting sources. The low heat output is an important feature in the present context, because the lights can be placed at a small distance above the plants. Furtermore, depending on the manufacture, LEDs can direct light at a narrow angle, ensuring that all available energy is diverted towards the plant [Bula et al., 1991, Bourget, 2008, Massa et al., 2008, Morrow, 2008].

3.3 LED Experiments

Various commercial LED units were compared in a test rig using a broad wavelength spectrum sensor. The selection was based on performance against energy consumption, whilst accounting for the intensity requirements of the case study plant species. Two tests were completed, as follows.

In the first case, intensity was measured at the area around the light unit. Here, the intensity is denoted as Photosynthetic Photon Flux (PPF) and its unit of measurement is $\mu mols/m^2/s$ in terms of photons, as shown in Fig. 3, or $J/m^2/s$ in terms of energy [Sager and McFarlane, 1997]. These units are valid within the photosynthetically active radiation range (i.e. 350–850nm). Measurements were taken at distances of 10, 20 and 40cm, while the area of measurement was 90cm × 110cm. Fig. 3 shows the light distribution of the LED units chosen for the pilot grow–cell for these distances. It can be observed that, depending on the distance above the plant, various combinations of lighting area and intensity can be applied.

Secondly, a spectrometer was used to derive the spectral output. Fig. 4 shows the spectral output of the LED unit selected for the demonstrator grow–cell. This is essentially a blue light (hence the maximum intensity at 448nm) but phosphor coating has been applied to the LEDs so that the resulting colour is white, with additional light for photosynthesis coming from the green and orange–red regions of the visible spectrum.

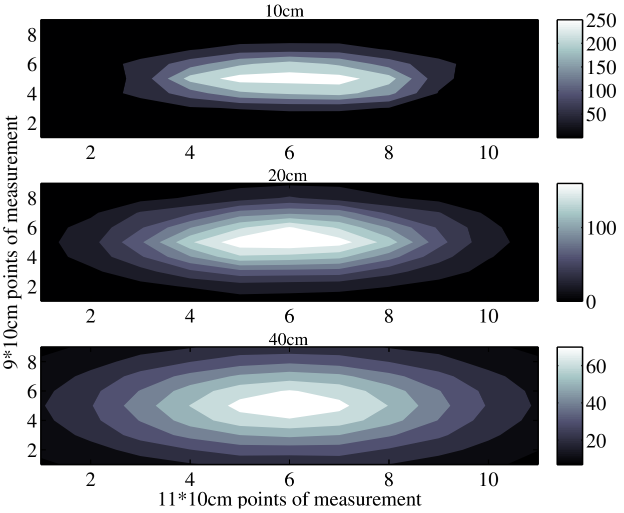

Fig. 3. Light distribution of selected LED unit.

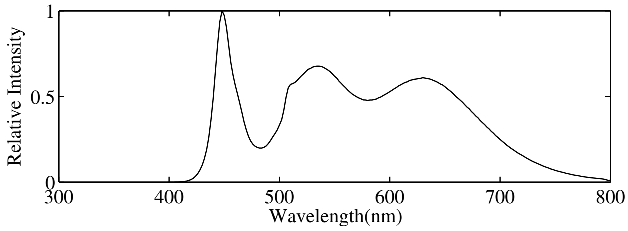

Fig. 4. Spectral output of selected LED unit.

In total, 220 lights will be utilised in the demonstrator grow–cell, in order to cover the overall growing area. This immediately indicates a significant amount of power consumption. In order to reduce excess energy consumption and subsequent operational costs, a variable power supply system is being developed to drive the lights. Fig. 5 shows the intensity variation when increasing the output voltage from 35 to 48VDC. The measurements were taken at 20cm below the center of the light. As shown, very little increase is observed between 42VDC and 48VDC (11%). This clearly indicates that excessive power consumption can be prevented while still having adequate light quantity for the plants. For example, if all the lights were to operate at 42VDC at a daily photoperiod of 12 hours, it would be possible to save 42KWh per day.

Hence, it is possible to save approximately 15W per unit when lights operate at 42VDC while still having a light output of $159\mu mols/m^2/s$. Extrapolating from this, Fig. 6 shows the potential carbon dioxide footprint reduction per year (CO_2 factor: 0.517 Kg CO_2/KWh), when all the lights are used for a 12 hour daily photoperiod. It can be seen, for example, that 8 to 14 tons per year can be removed from the total footprint if the lights are operated within the range of 39 to 42VDC.

3.4 Temperature/Humidity Monitoring

Within the prototype unit, temperature and humidity data will be collected using an array of sensors. More specifically, 32 portable temperature and humidity loggers are being equally distributed in order to capture the gradients within the growing airspace. For the chosen Easylog USB sensors (Lascar Electronics Inc), there is a storage capacity of 16382 readings, with a user selected sampling rate up to 1 sample per second. However, a sampling rate of 5 minutes is selected in order to allow for the sensors to collect data for the full growth cycle of the case study plant species. The accuracy of these particular sensors is ±0.3C and ±2% RH. Similar portable sensors have been used by e.g. Herberger and Ulmer [2012]. In addition, temperature and humidity information will be collected from the existing commercial refrigeration unit, and an additional portable sensor will be used to capture ambient conditions.

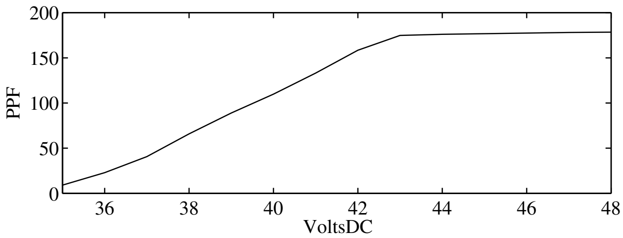

Fig. 5. Light intensity vs voltage increase.

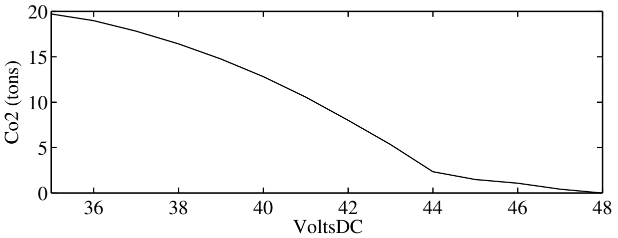

Fig. 6. CO2 savings per year vs voltage increase.

4. EXPERIMENTAL DATA

Whilst the grow–cell test unit is under development, the authors are investigating data collection issues and thermal modelling for two related case studies, one laboratory, the other agricultural:

- *Lancaster University forced ventilation test chamber.* With widespread application to e.g. animal houses, supermarket freezers and air–conditioning systems, the Lancaster environmental control test facility includes an array of 30 thermocouples and airflow sensors in an enclosed 1m by 1m by 2m airspace. Actuators include two axial fans and a heating system, with National Instruments data–logging hardware/software [Stables and Taylor, 2006].
- *Fodder crop farm.* Sensors were distributed around a small building used for growing animal fodder. A commercial HVAC system with inlet ducting at the ceiling is complemented by underfloor heating, whilst irregation occurs every two hours by means of spray nozzles. Although the details are beyond the scope of the present article, one purpose was to gain experience of and to evaluate the above data–logging and monitoring system for a straightforward practical example [Tsitsimpelis, 2013].

With regard to the fodder barn, Fig. 7 compares the HVAC inlet and outside temperatures, highlighting the bang–bang nature of the commercial control system. The results also show wide temperature distributions within the building, with some well mixed zones and other stagnant zones, as alluded to above. By contrast, the Lancaster chamber allows for a wide range of planned experiments in order to either suppress or activate deadzones and other inherent nonlinearities in the system e.g. to evaluate different modelling approaches.

An illustrative experiment for the Lancaster chamber is shown in Fig. 8. Here, the voltage input associated with the outlet fan is varied at random times between several randomly chosen magnitudes (middle subplot), whilst the heater input follows a standard pseudo–random binary signal (i.e. on–off). Temperature data were collected at a sampling rate of 60s from 30 locations within the test chamber, as shown in the upper subplot of Fig. 8. A visual inspection of all the responses suggests that it is possible to derive broadly two zones of relatively similar responses, i.e. a group of 10 thermocouples near the top of the chamber, and the remaining thermocouples representing the middle and lower part of the chamber. This result may suggest that the chamber can be divided into two (relatively) well–mixed 'conceptual' zones for the purposes of modelling [Agbi et al., 2012].

The average temperatures for each of these zones are illustrated in the upper subplot of Fig. 9, in which the thin trace (i.e. warmer temperatures) represents the lower zone. The following linear Transfer Function model, estimated using the Refined Instrumental Variable (RIV) algorithm of the CAPTAIN Toolbox [see Taylor et al., 2007, 2013, Young, 2011, and the references therein] provides a reasonable fit to experimental data, as illustrated by the lower subplot of Fig. 9,

$$y_1(k) = \frac{b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1}} u_1(k) + \frac{d_1 z^{-1}}{1 + a_1 z^{-1}} u_2(k) \qquad (1)$$

where $y_1(k)$ is the average temperature of the lower zone, while $u_1(k)$ and $u_2(k)$ are the heater and fan inputs respectively, and z^{-1} is the backward shift operator, i.e. $y(k)z^{-1} = y(k-1)$. For the present example, the parameter estimates are $b_1 = 0.6296$, $b_2 = -0.5000$, $d_1 = -0.1023$, $a_1 = -0.9381$. This model explains 94% of the variance of the data, as indicated by the coefficient of determination ($R_T^2 = 0.9460$). In the lower subplot of Fig. 9, the thin trace represents the data and the thick trace the simulation response of the model (1).

However, the utility of this model for control system design is relatively limited, since it depends on the assumption of well–mixed zones and the particular airflow pattern that emerges for this experiment. Significantly, other input sequences suggest different airflow patterns and hence zones. There is some evidence, for example, that the corners of the chamber should be treated as a separate element whilst, for the full scale grow–cell system, there are expected to be several physical (e.g. HVAC inlet, plant growing area, access area) and conceptual (e.g. along the length of the growing area) zones.

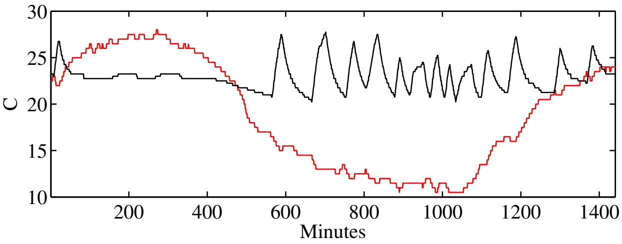

Fig. 7. Fodder barn ambient and incoming air temperature.

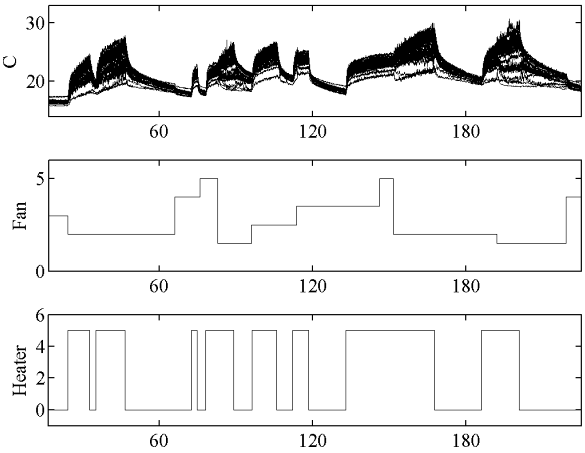

Fig. 8. Illustrative heating/ventilation experiment.

In this regard, the authors are developing a quantitative approach for the derivation of suitable zones, with respect to a specified gradient tolerance. Since the focus of the present article is an overview of the grow–cell system, rather than modelling *per se*, the details will be reported in future articles. Nonetheless, to give an example, Fig. 10 shows the correlation between one particular thermocouple and all the other thermocouples, for the present experiment. Fig. 10 is a schematic representation of the Lancaster ventilation chamber, and the numerical values indicate the location of the thermocouples. In fact, the lower the numerical value shown, the more highly correlated the response is to the reference thermocouple. The latter reference thermocouple (arbitrarily chosen for the purposes of this example) is near the top left corner of Fig. 10, and is represented by a '0' (i.e. exactly correlated with itself). The usefulness of this approach will be assessed within the context of formulating state–dependent parameter thermal models [Stables and Taylor, 2006, Taylor et al., 2011]. In the future, these will be part of a zonal temperature control system for the grow–cell.

5. CONCLUSIONS

This article has briefly reviewed the concept and potential horticultural advantages of a grow–cell, and has described preliminary work in relation to a demonstration unit being developed by the authors and collaborating industry partner. In particular, the article has described the development of the conveyor control system, summarised research into LED light selection, and introduced the data collection approach. Finally, the temperature modelling approach is illustrated using experimental data from a laboratory scale forced ventilation test chamber.

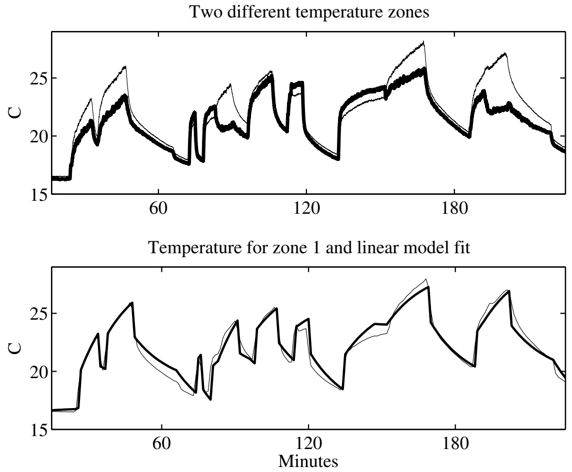

Fig. 9. Dual–zones for heating/ventilation experiment.

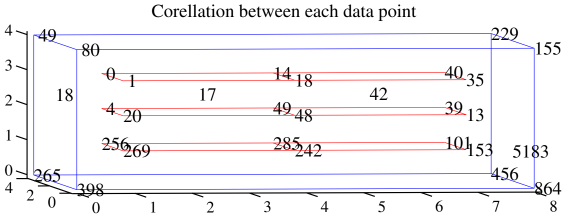

Fig. 10. Correlation between thermocouples

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