# CONCEPTUAL EVALUATION OF A DUAL-PIPE COUNTER-FLOW CONFIGURATION FOR IMPROVING TEMPERATURE UNIFORMITY IN LOCAL CROWN COOLING OF GREENHOUSE CROPS


## Summary

A one-dimensional energy balance model with separated crown-contact and air-loss heat exchange was used to evaluate a dual-pipe counter-flow concept for local crown cooling of greenhouse strawberry crops. Two chilled-water loops run in opposite directions along the cultivation bed so that each crown contacts thermally complementary pipe sections. At the same total flow rate, the dual configuration reduced crown temperature variation from 1.13 K to 0.02 K and lowered total electrical power by 21%. The improved uniformity enables flow reduction from 0.167 to 0.048 L s$^{-1}$ while keeping average crown temperature below 25 °C, yielding a 34% reduction in cooling load and 41% reduction in total electrical consumption. Experimental validation of pipe–crown contact conditions is identified as the key remaining step.


*Keywords: greenhouse cooling, strawberry crown, chilled-water pipe, counter-flow, temperature uniformity*

*Field of application for the findings: The findings contribute to both academic literature and the development of greenhouse building cooling technologies by proposing an efficient local cooling concept.*

*Addressed audience:* ***academicians, researchers, greenhouse building developers, and horticultural technology developers***

## 1. Introduction

Local crown cooling with chilled-water pipes is an energy-efficient method for protecting heat-sensitive greenhouse crops such as strawberries. A typical system circulates chilled water (20 °C) through a single U-loop pipe (PE or stainless steel, 16 mm OD, 50 m bed length) placed in contact with the plant crowns. However, the water temperature rises progressively as it absorbs heat from the crowns and surrounding air (~30 °C), creating a longitudinal gradient in crown temperature. This limits the extent to which the flow rate can be reduced, since lower flow exacerbates the gradient and causes downstream crowns to exceed the target (25 °C).

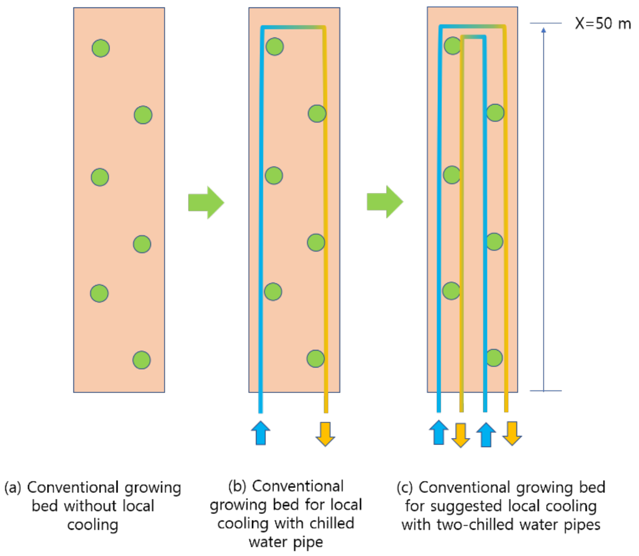


**Fig. 1: Conventional single-pipe layout (left) and proposed dual-pipe counter-flow concept (right) for local crown cooling.**

The proposed dual-pipe counter-flow concept (Fig. 1) places two independent U-loop pipes in opposite directions along the cultivation bed, each carrying half of the total flow. Each crown contacts both pipes from its inner and outer sides, experiencing the average of a cold-section and a warm-section pipe at every longitudinal position. The resulting cross-cancellation markedly reduces the spatial temperature gradient. The optimized case was defined as the minimum-total-power condition subject to an average crown temperature not exceeding 25 °C.

## 2. Model

A one-dimensional energy balance was formulated for the pipe water temperature. The pipe exchanges heat with the strawberry crown (at $T_{crown}$) and the surrounding air (at $T_{amb}$) through separate pathways:

$$\dot{m}c_p\, dT_w/dx = -UP_{crop}(T_w - T_{crown}) - UP_{air}(T_w - T_{amb}) \qquad \text{(eq. 1).}$$

$UP_{air}$ = 0.23 W m$^{-1}$ K$^{-1}$ was estimated from a natural convection coefficient of 5 W m$^{-2}$ K$^{-1}$ (Incropera and DeWitt, 1996) over the exposed pipe surface. An apparent overall heat transfer coefficient $UP_{apparent}$ = 3.28 W m$^{-1}$ K$^{-1}$ was obtained by fitting an exponential temperature profile to the field-measured inlet–outlet ΔT of 2.1 K at 0.167 L s$^{-1}$ (Rural Development Administration, 2014), assuming the ambient temperature (30 °C) as the sole driving temperature. $UP_{crop}$ was then approximated as $UP_{apparent} - UP_{air}$ = 3.05 W m$^{-1}$ K$^{-1}$.

For the single pipe configuration, a zigzag crown model reflects the alternating plant arrangement in elevated-bed cultivation, where each crown contacts only the supply or return leg of the pipe. The crown temperatures are

$$T_{c,s} = w_1T_s + (1 - w_1)T_{amb} \quad \text{(supply side)}\ ,\ T_{c,r} = w_1T_r + (1 - w_1)T_{amb} \quad \text{(return side)} \qquad \text{(eq. 2)}$$

, where $w_1$ = 0.559 was calibrated so that the predicted average crown temperature matches the representative field value of 25 °C (Rural Development Administration, 2014).

For the dual configuration, each crown contacts two of the four pipes simultaneously. Crown row A contacts the supply leg of pipe 1 and the return leg of pipe 2, while crown row B contacts the return leg of pipe 1 and the supply leg of pipe 2:

$$T_{c,A} = w_2 \times (T_{1s} + T_{2r})/2 + (1 - w_2) \times T_{amb}\ ,\ T_{c,B} = w_2 \times (T_{1r} + T_{2s})/2 + (1 - w_2) \times T_{amb} \qquad \text{(eq. 3)}$$

Due to the counter-flow symmetry, $(T_{1s}+ T_{2r})/2 = (T_{1r}+ T_{2s})/2$ at every position, so $T_{c,A}= T_{c,B}$, yielding uniform crown temperature along the bed. The coupling weight was estimated as $w_2= 2r/(2r+1)$ with $r = w_1/(1-w_1)$, assuming that two pipes provide twice the contact conductance of a single pipe, giving $w_2$= 0.717. This parameter is the most influential in the model and its actual value requires experimental verification.

The cooling load is $Q_{cool} = \dot{m}c_p\Delta T$, and total electrical power is the sum of chiller power ($Q_{cool}$/COP, assumed COP = 2.75) and pump power. The baseline single-pipe model was validated against field data: predicted average crown temperature of 25.0 °C and inlet–outlet ΔT of 2.0 K, compared with measured values of 25.0 °C and 2.1 K (Rural Development Administration, 2014).

## 3. Results and discussion

At the same total flow rate (0.167 L s$^{-1}$), the dual-pipe configuration reduced crown temperature variation from 1.13 K (PE) and 1.16 K (SS) to approximately 0.02 K—a 98% improvement (Tab. 1). The cooling load decreased by 15–16%, because each pipe carries only half the flow, reducing the total heat absorbed from the warm surroundings over the 50 m path. Combined with the pump power reduction from flow splitting, total electrical consumption fell by 21–22%.

The temperature uniformity enables significant flow reduction. At the optimized total flow of 0.048 L s$^{-1}$ (2.9 L min$^{-1}$), the average crown temperature remained below 25 °C while the cooling load dropped by 34% and pump power became negligible (< 1 W). The resulting total power saving was approximately 41% for both pipe materials. In contrast, the conventional single-pipe configuration cannot reduce its flow below 0.167 L s$^{-1}$ without exceeding the 25 °C crown temperature constraint. Fig. 2 shows representative water and crown temperature profiles for the PE pipe cases.

## 4. Conclusions

The energy savings arise from two coupled effects: (i) the counter-flow arrangement cross-cancels the longitudinal temperature imbalance, and (ii) the reduced per-pipe flow decreases the total heat absorbed from the warm surroundings, directly reducing the cooling load. The first mechanism enables the second by allowing substantial flow reduction without the average crown temperature exceeding the target.

The present analysis involves several simplifying assumptions, including the decomposition of the apparent heat transfer coefficient, the crown–pipe coupling weights, and the use of a single reported crown temperature as the calibration target. More detailed modelling with refined treatment of these parameters is therefore needed before drawing definitive design conclusions. Small-scale experiments are planned to validate the model predictions and to quantify the effective pipe–crown thermal contact under dual-pipe operation.

**Tab. 1: Performance comparison for PE and SS pipes (inlet temperature 20 °C fixed).**

| Pipe | Config. | Flow ($L\ s^{-1}$) | Avg. crown (°C) | ΔT (K) | Q_cool (W_th) | Chiller (W_e) | Pump (W_e) | Total (W_e) | Saving (%) | Note |
|---|---|---|---|---|---|---|---|---|---|---|
| PE | Single | 0.167 | 25.00 | 1.131 | 1408 | 512 | 60 | 572 | — | ref. |
| PE | Dual | 0.167 | 23.50 | 0.019 | 1195 | 435 | 15 | 450 | 21 | same flow |
| PE | Dual opt. | 0.048 | 24.94 | 0.179 | 931 | 339 | 0.4 | 339 | 41 | optimized |
| SS | Single | 0.167 | 25.01 | 1.157 | 1440 | 524 | 60 | 584 | — | ref. |
| SS | Dual | 0.167 | 23.51 | 0.020 | 1216 | 442 | 15 | 457 | 22 | same flow |
| SS | Dual opt. | 0.048 | 24.98 | 0.186 | 942 | 343 | 0.4 | 343 | 41 | optimized |

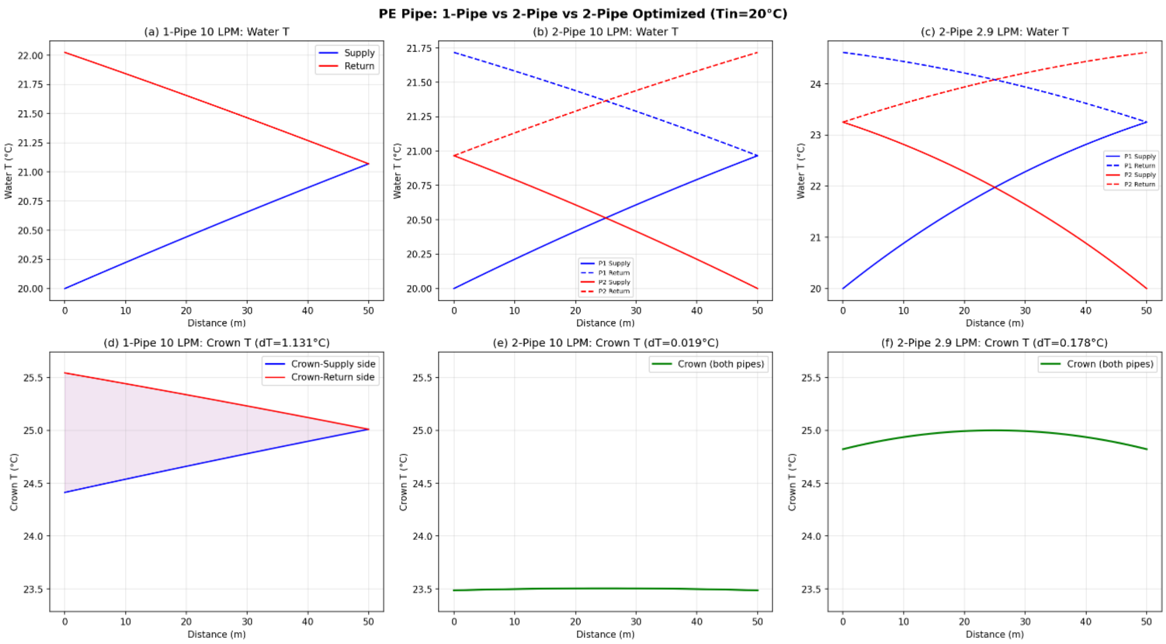

**Fig. 2: Comparison of water temperature and crop crown temperature for PE pipe cases.**

## 5. References


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