

### Supplementary Materials

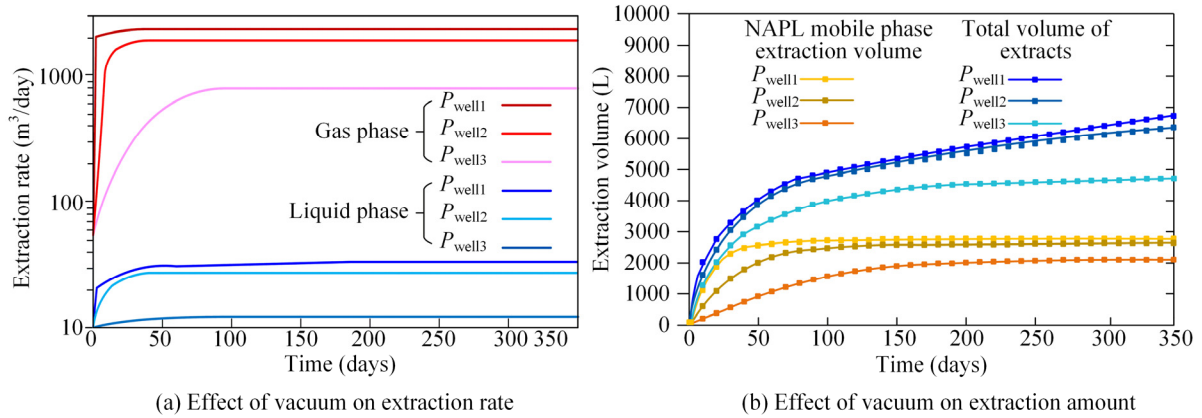


Fig. S1. Effects of different vacuum levels on MPE extraction efficiency.

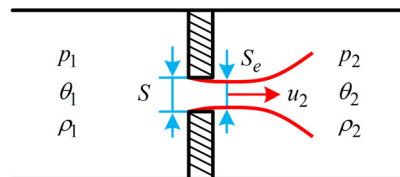


Fig. S2. Equivalent modeling of regulating valves.

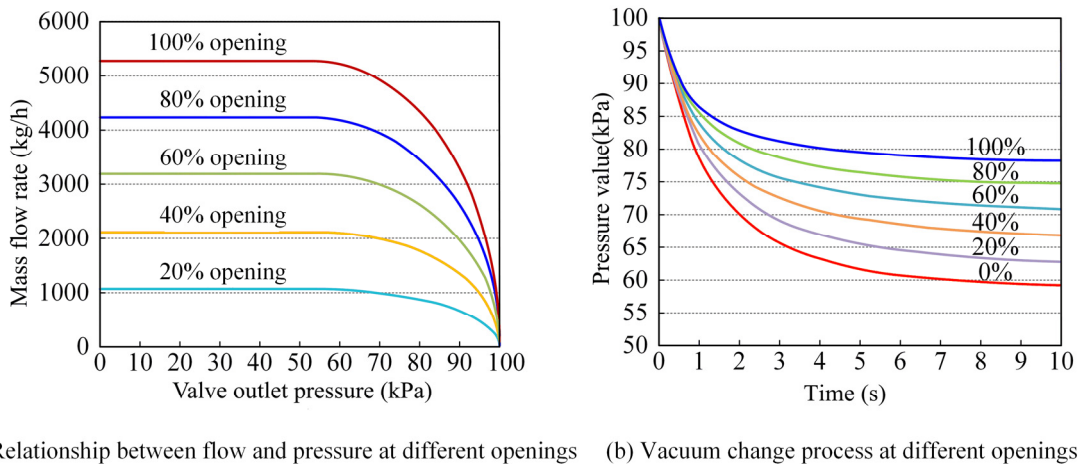


Fig. S3. Effects of regulating valve opening on extraction vacuum.

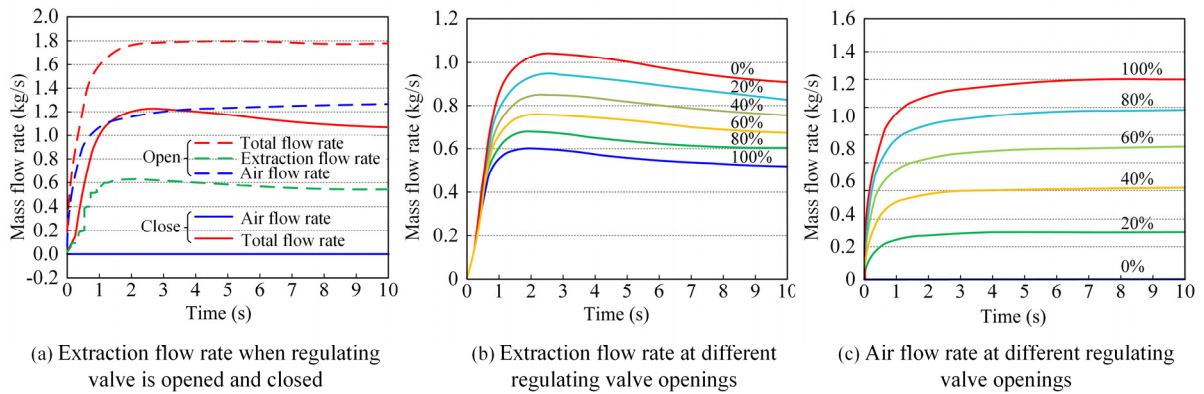


Fig. S4. Effects of regulating valve openings on extraction flow rate.

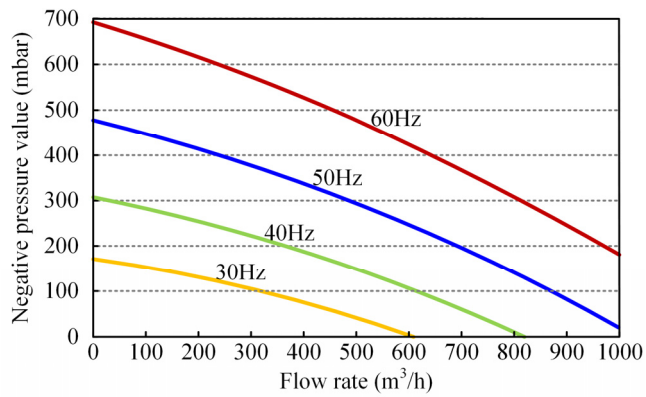


Fig. S5. Pressure-flow curves at different frequencies.

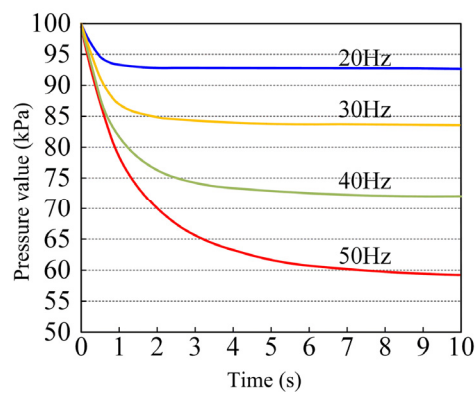


Fig. S6. Variation of vacuum level at different frequencies.

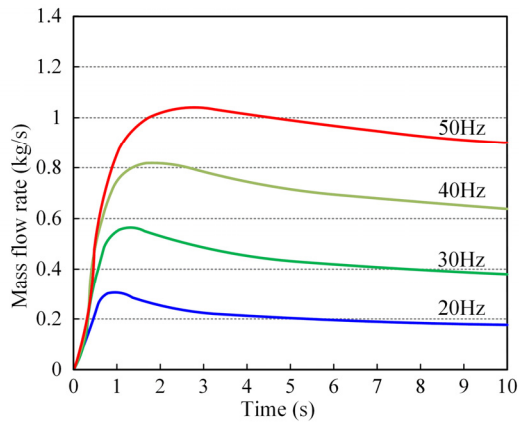


Fig. S7. Extraction flow curves at different frequencies.

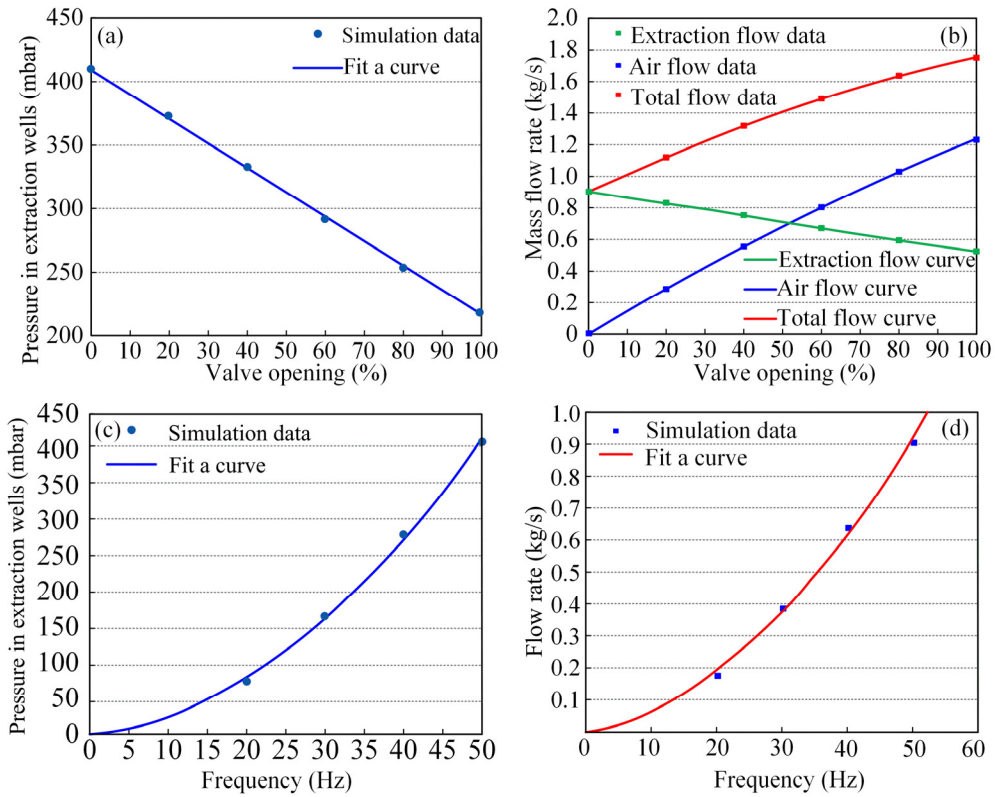


Fig. S8. Fitted Curve.

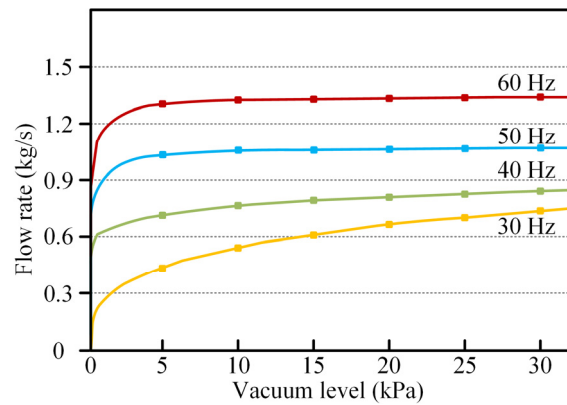


Fig. S9. Results of the optimization model

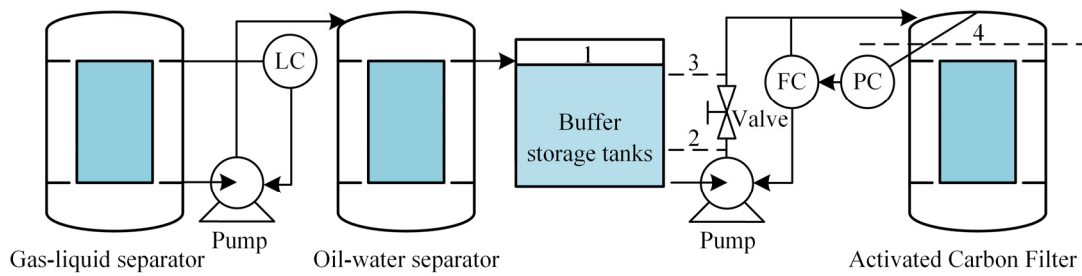


Fig. S10. Equivalent diagram of liquid phase transport for MPE equipment.

Table S1. Parameters of actual engineering.

Parameters	value	Parameters	value
$n_0$	2892 rpm	$a$	0.3725
$L$	3 m	$b$	0.01
	1.5	$c$	-0.0025
$\rho$	998 kg/m <sup>3</sup>	$Q_0$	0.13 m <sup>3</sup> /s
$\lambda$	0.16		1.1m

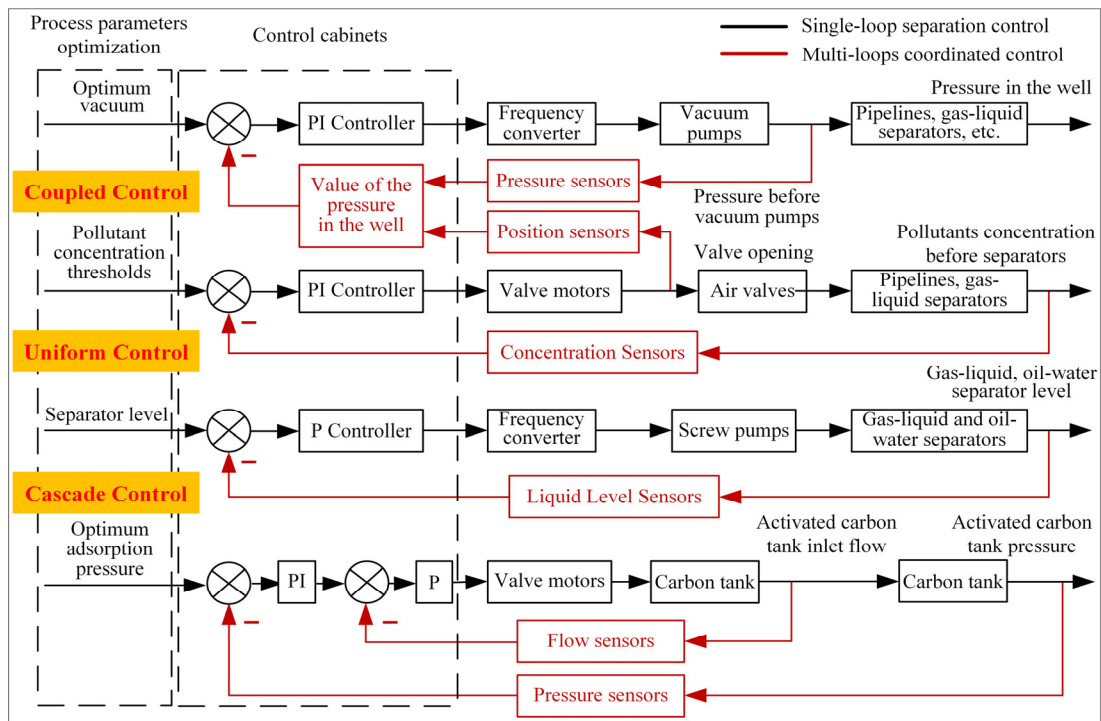


Fig. S11. MPE multi-loops coordinated control strategy.

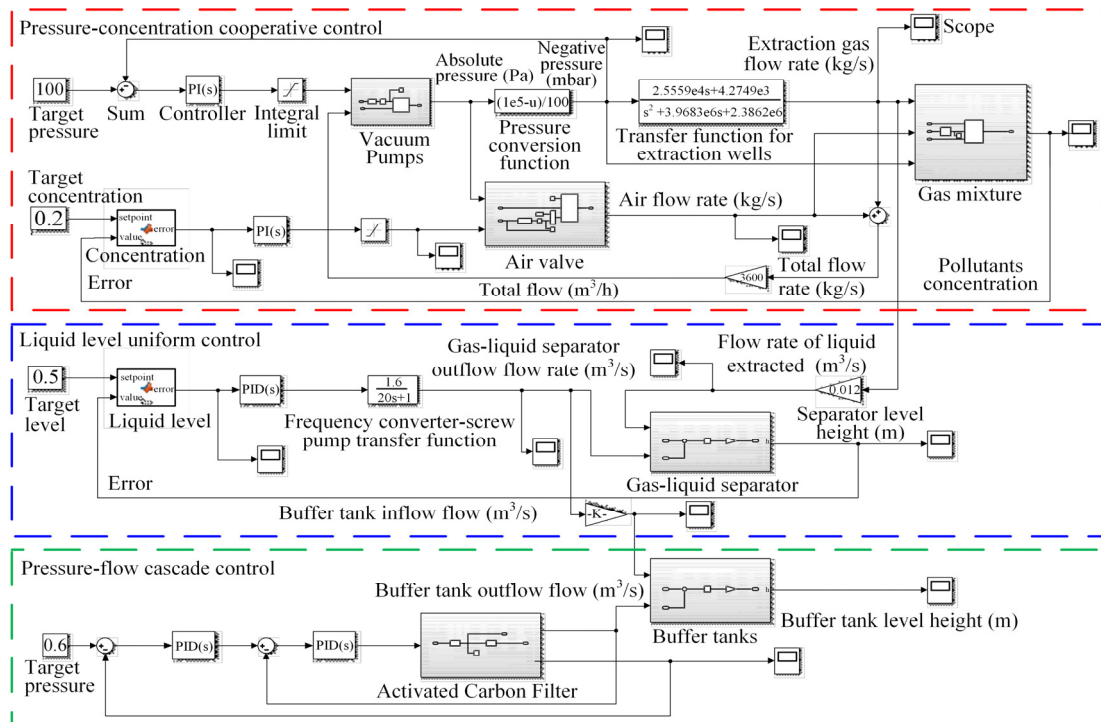
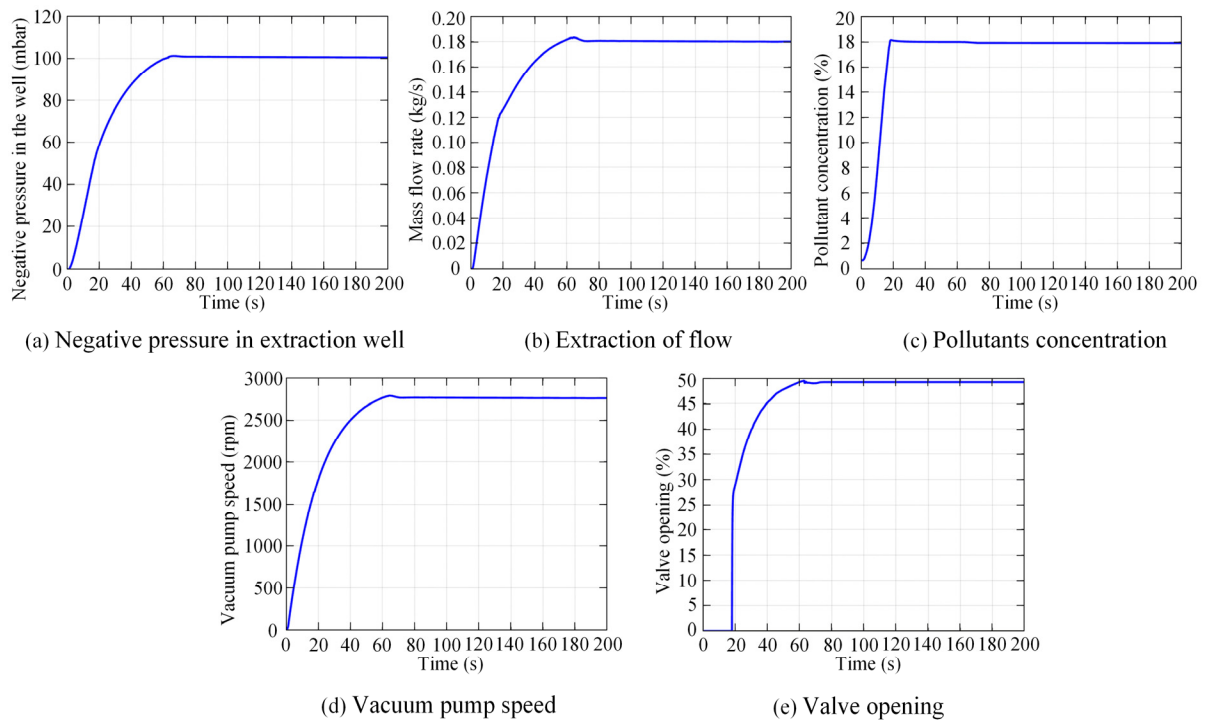
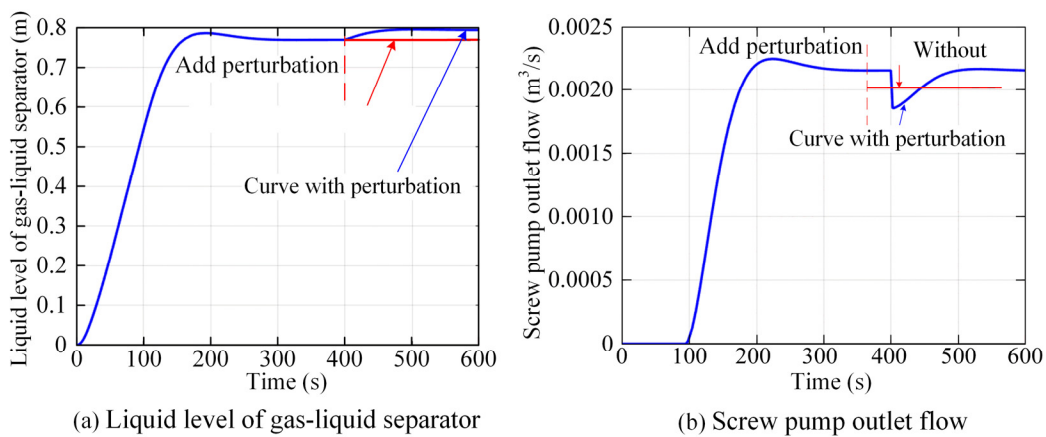


Fig. S12. Simulink simulation of MPE control system.



**Fig. S13.** Control results of extraction vacuum, extraction flow rate, and pollutants concentration.



**Fig. S14.** Control results of separator liquid level and outlet flow rate of pumps.

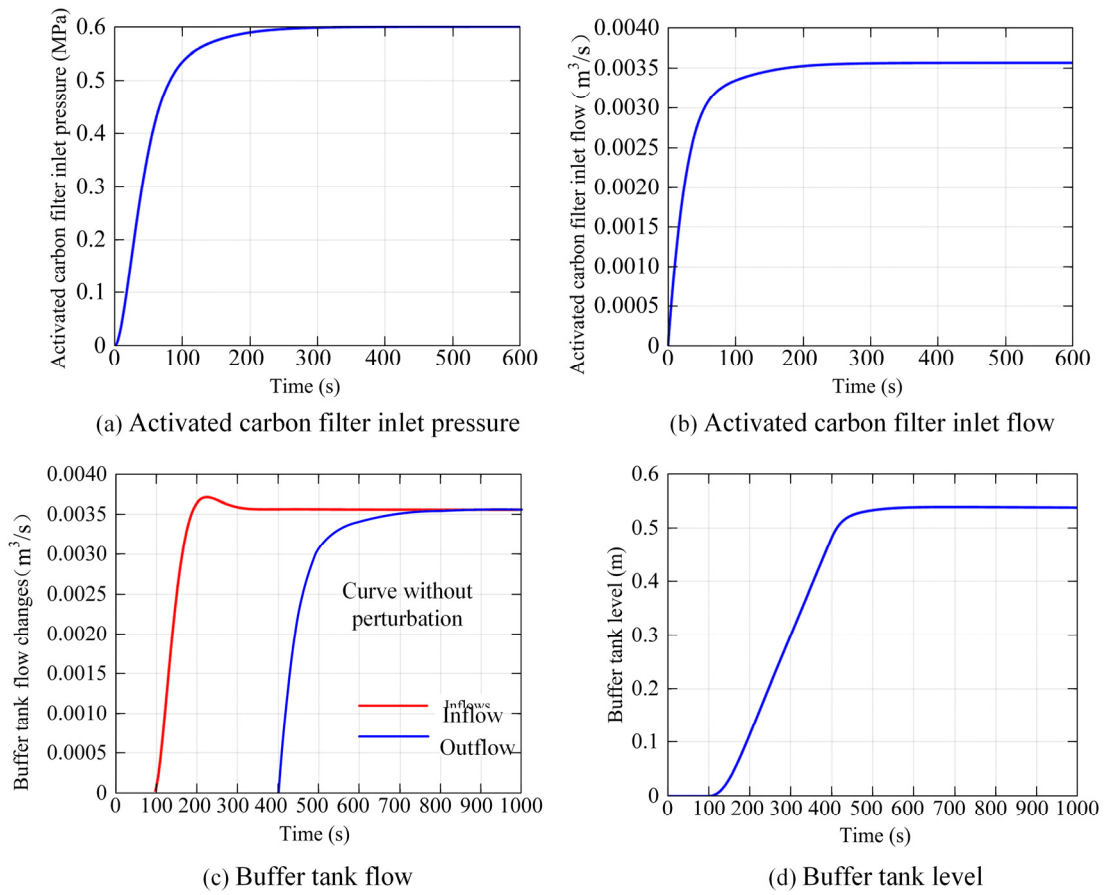


Fig. S15. Control results of activated carbon filter inlet flow and pressure.

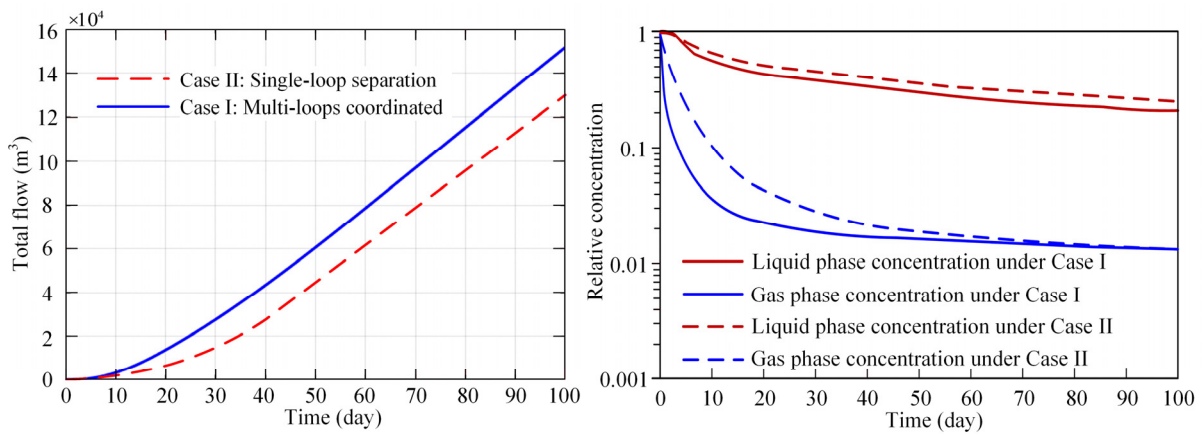


Fig. S16. Results of the two cases.