

CLAIMS

1. An ultraviolet (UV) reactor comprising:
 - a fluid conduit comprising a fluid inlet, a fluid outlet, and a fluid flow channel located between the inlet and the outlet, the fluid flow channel extending in a longitudinal direction for permitting a flow of fluid in a longitudinal direction therethrough;
 - a solid-state UV emitter configured to emit a radiation along a radiation path from an emission region of the solid-state UV emitter; and
 - a plurality of lenses positioned in the radiation path to direct at least some of the radiation into the fluid flow channel, the plurality of lenses comprising at least:
 - a converging lens with a first convex surface adjacent to the solid-state UV emitter; and
 - a second lens with a second convex surface spaced apart from the first convex surface, and a focal point before the plurality of lenses that is spaced apart from the emission region of the solid-state UV emitter,
 - wherein, when the solid-state UV emitter is emitting the radiation, an average, over a longitudinal dimension of the fluid flow channel, radiation fluence rate profile of the radiation emitted from the emission region of the solid-state UV emitter and refracted by the plurality of lenses over a portion of a cross-section of the fluid flow channel after the plurality of lenses is positively correlated with an elliptic paraboloid shape generally aligned with the radiation path.
2. The UV reactor of claim 1, wherein the emission region is spaced apart from the focal point in the longitudinal direction of the fluid flow channel, the emission region and the focal point are on a common longitudinal axis of the fluid flow channel, the focal point is spaced apart from the plurality of lenses by a first distance, the emission region is spaced apart from the plurality of lenses by a second distance, and the first distance is greater than the second distance.

3. The UV reactor of claim 1 or 2, wherein at least the second lens of the plurality of lenses is movable to modify the average radiation fluence rate profile of the portion of the cross-sectional area.
4. The UV reactor of claim 1, 2, or 3, wherein the portion of the cross-section comprises more than 70% of the surface area of a total cross-section of the fluid flow channel.
5. The UV reactor of claim 1, 2, 3, or 4, wherein a first average radiation fluence rate profile of the radiation at cross-sectional locations relatively proximate to a cross-sectional center of the fluid flow channel is greater than a second average, over the longitudinal dimension of the fluid flow channel, radiation fluence rate profile of the radiation at cross-sectional locations relatively distant from the cross-sectional center of the fluid flow channel.
6. The UV reactor of any one of claims 1 to 5, wherein the solid-state UV emitter comprises one or more of:
 - at least one UV light-emitting diode (UV-LED); and
 - at least one thin dielectric film.
7. The UV reactor of any one of claims 1 to 6, wherein the plurality of lenses comprises one or more of: a converging lens, a diverging lens, and a collimating lens.
8. The UV reactor of any one of claims 1 to 7, wherein:
 - the UV reactor comprises a plurality of solid-state UV emitters; and
 - the plurality of lenses comprise a lens corresponding to each one of the plurality of solid-state UV emitters and positioned to direct at least some of the radiation emitted from an emission region of the corresponding one of the plurality of solid-state UV emitters into the fluid flow channel.

9. The UV reactor of any one of claims 1 to 7, wherein:
 - the solid-state UV emitter comprises a plurality of solid-state UV emitters configured to emit the radiation along the radiation path from an emission region of each one of the plurality of solid-state UV emitters; and
 - the plurality of lenses comprise at least one shared lens positioned relative to the emission regions of the plurality of solid-state UV emitters to direct at least some of a sum of the radiation into the fluid flow channel.
10. The UV reactor of any one of claims 1 to 9, comprising one or more flow-restraining elements located in the fluid flow channel to modify a velocity of the fluid flowing in the fluid flow channel.
11. The UV reactor of claim 10, wherein the one or more flow-restraining elements include one or more of: a static mixer, a vortex generator, a baffle, an adjustable element, a perforated material, and a porous material.
12. The UV reactor of claim 10 or 11, wherein the one or more flow-restraining elements include a nozzle element configured to provide a non-uniform fluid velocity profile at a center of the cross-section of the fluid channel.
13. The UV reactor of claim 10, 11, or 12, wherein the one or more flow-restraining elements include an adjustable element, and a porosity of the at least one flow-restraining element is adjustable to be more or less porous.
14. The UV reactor of any one of claims 1 to 13, wherein the solid-state UV emitter comprises:
 - a first solid-state UV emitter configured to emit a first radiation along a first radiation path from a first emission region of the first emitter; and
 - a second solid-state UV emitter configured to emit a second radiation along a second radiation path from a second emission region of the second emitter.

15. The UV reactor of claim 14, wherein the first radiation and the second radiation include different wavelengths.
16. The UV reactor of any one of claims 1 to 15, wherein the plurality of lenses are integrally packaged with the solid-state UV emitter.
17. The UV reactor of any one of claims 1 to 16, wherein, when the fluid is passed through the fluid flow channel, the fluid flow channel defines an average, over the longitudinal dimension of the fluid flow channel, longitudinal direction fluid velocity profile over the portion of the cross section of the fluid flow channel, the average fluid velocity profile being positively correlated with the average radiation fluence rate profile.
18. The UV reactor of any one of claims 1 to 17, wherein the elliptic paraboloid comprises an axis aligned with a central axis of the radiation path and a central axis of the fluid flow channel.
19. The UV reactor of claim 18, wherein the elliptic paraboloid comprises maximum radiation fluence rates at a central area of the radiation path.
20. A method of using the UV reactor of any one of claims 1 to 19, the method comprising:
 - causing the flow of fluid to flow through the fluid conduit, thereby causing the flow of fluid to have an average, over the longitudinal dimension of the fluid flow channel, longitudinal direction fluid velocity profile over the portion of the cross section of the fluid flow channel; and
 - causing the radiation emitted by the solid-state UV emitter to pass through the plurality of lenses and into the fluid flow channel, thereby producing the average radiation fluence rate profile over the portion of the cross section of the fluid flow channel, wherein the average radiation fluence rate profile over the portion of the cross section of the fluid flow channel is positively correlated with the average fluid velocity profile.